Group Art Unit: 2884
Examiner: Lee, S.

Atty. Ref.: H 2182

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants	:	Martin Klein et al.
Appl. No.	:	10/047,556
Filed	:	October 23, 2001
For	:	DETECTOR

MS Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

RULE 132 DECLARATION

Sir:

I, Martin Klein, am a citizen of Germany and reside at Glauchauer Weg 10, 68309 Mannheim (new address) (old address: Seckenheimer Strasse 46 B, Mannheim 68165), Germany. I have a doctorate degree in Physics and I am currently employed by Heidelberg University.

I am one of the two named inventors in the above-captioned United States patent application and I am familiar with my patent application. I also studied and am familiar with U.S. Patent No. 6,429,578 which issued to Danielsson et al.

I conducted simulation analyses to compare absorption efficiencies of three different converter devices. It has been my experience that the simulation program I used provides a close approximation of actual tests. Additionally, the simulation analysis is very good for comparing the absorption efficiencies of different converter devices.

The Danielsson et al. patent focuses on the detection of X-rays. As a result, my simulation analyses were carried out to compare absorption efficiency for X-rays having energies between 10 keV and 150 keV.

The first converter device simulated in my analysis was a conventional GEM foil having copper electrodes with thicknesses of 5 micrometers disposed on opposite respective sides of an insulator. The absorption efficiencies for that simulation are represented by the lowermost line on the graph attached to this Declaration.

The second converter device that was subject to my simulation analysis had an additional layer of copper of 5 micrometer thickness on one of the copper electrodes of the conventional GEM foil used in the first analysis. As a result, the second simulation had a copper layer of 10 micrometers thick on one side of the insulator. This second simulation analysis was intended to simulate the embodiment of Danielesson et al. set forth in claim 11 of the Danielsson et al. patent. Absorption efficiencies for that second simulation are represented by the center line in the graph.

The third converter device simulated in my analysis had a 5 micrometer thick layer of gold on the copper electrode on one side of the conventional GEM foil. Thus, the third test sample conforms to the claims of my above-captioned patent application in that the converter layer is formed of a material different than the conductive layer on which the converter layer is arranged. My patent application focuses on neutron detection, and gold would not be chosen as a converter layer for neutron detection. Conversely, the converter layers used for neutron detection would not be used for X-ray detection. I chose a gold converter layer for the third simulation to provide a meaningful comparison to Danielsson

et al. The absorption efficiencies for the third simulation are shown by the uppermost line in the graph.

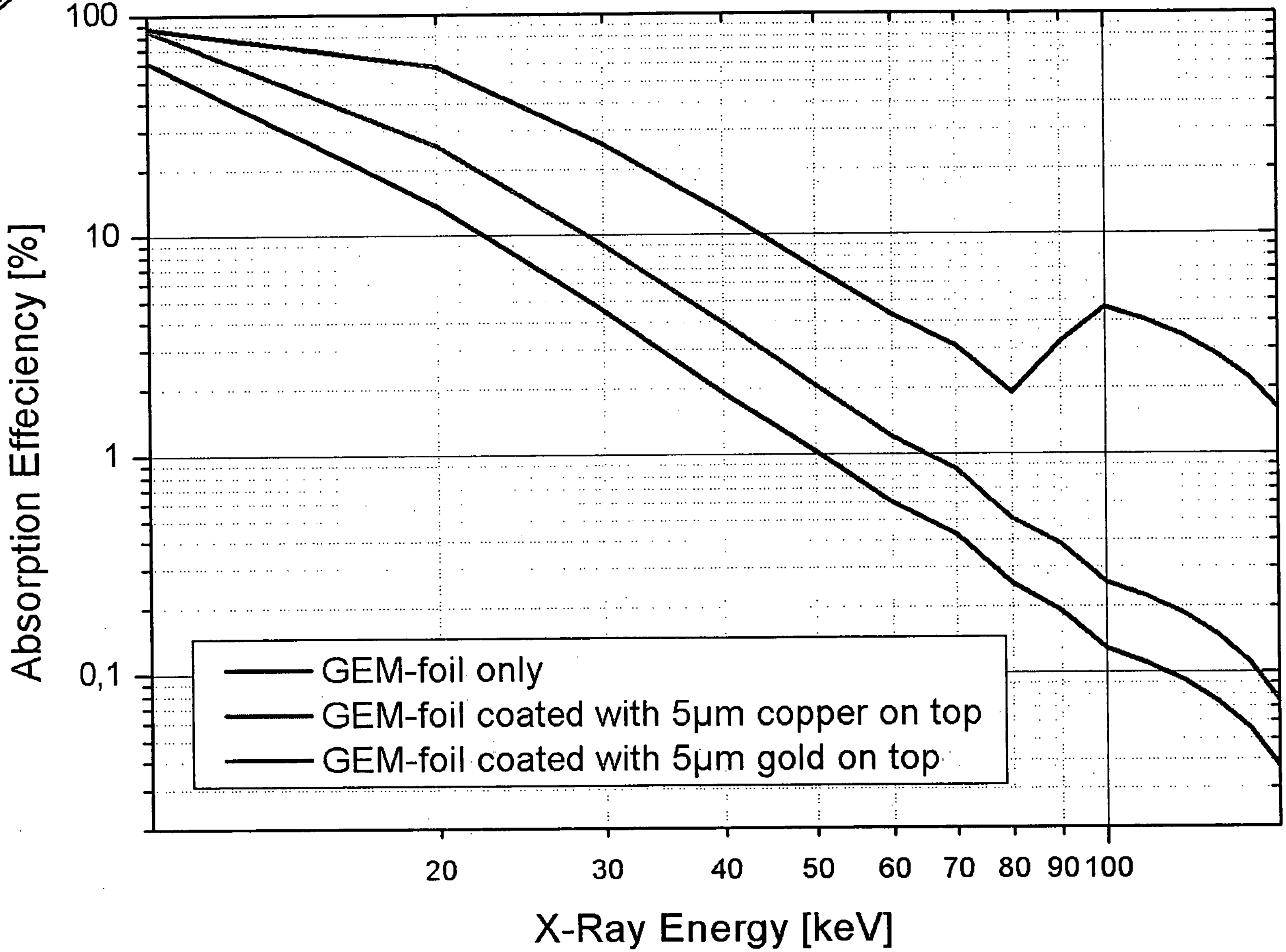
The vertical axis in the attached graph represents absorption efficiencies and is presented as a logarithmic scale. The attached graph shows very significantly enhanced absorption efficiencies for the third simulation (i.e., my claimed invention) as compared to either the first or second simulations. In particular, efficiencies achieved by the third simulation (the claimed invention herein) can be as much as ten times higher than the absorption efficiencies for the second simulation (Danielsson et al.). The magnitude of this enhanced absorption efficiency of the third simulation was greater than I would have expected.

I declare that all statements made herein on my own knowledge are true and that all statements made on information and belief are believed to be true and further that these statements are made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States code and that such willful false statements will jeopardize the validity of this application and any patent issued thereon.

Dr. Martin Klein

Martin Klein

Date: Heidelberg, 5. 5. 2006


100
10
1
0,1
Absorption Effeciency [%]
20
30
40
50
60
70
80
90
100
X-Ray Energy [keV]
GEM-foil only
GEM-foil coated with 5µm copper on top
GEM-foil coated with 5µm gold on top

United States Patent [19]

Gleason

[11] **3,956,654**

[45] **May 11, 1976**

[54] **LONG LIVED PROPORTIONAL COUNTER NEUTRON DETECTOR**

[75] Inventor: **Charles H. Gleason**, Horseheads, N.Y.

[73] Assignee: **Westinghouse Electric Corporation**, Pittsburgh, Pa.

[22] Filed: **Feb. 3, 1975**

[21] Appl. No.: **546,848**

[52] **U.S. Cl.** .... **313/61 D**; 313/93; 313/221; 313/224

[51] **Int. Cl.²** **H01J 17/20**; H01J 39/32

[58] **Field of Search** .... 313/61 D, 93, 221, 224; 250/390

[56] **References Cited**

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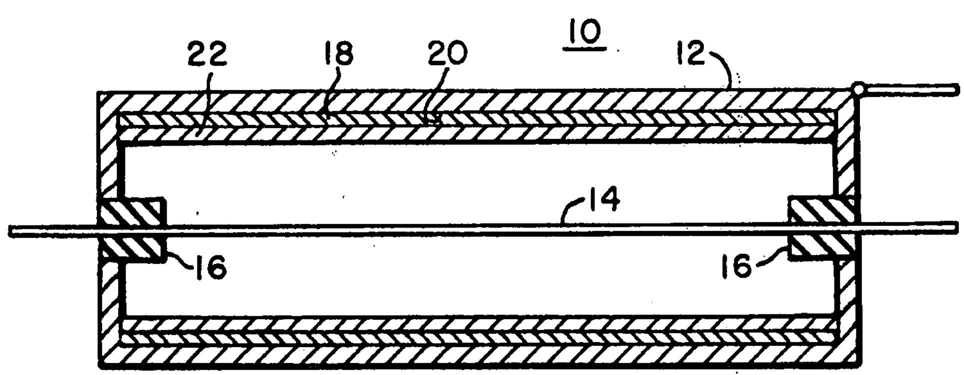
3,860,845	1/1975	Gleason et al.	313/61 D

Primary Examiner—Palmer C. Demeo
Attorney, Agent, or Firm—W. G. Sutcliff

[57] **ABSTRACT**

A proportional counter neutron detector in which the neutron absorptive material is isolated from the poly-atomic fill gas by a thin film of selected metal or metal oxide, which is substantially transmissive to neutrons, and is non-reactive with the dissociation products of the poly-atomic fill gas.

3 Claims, 1 Drawing Figure



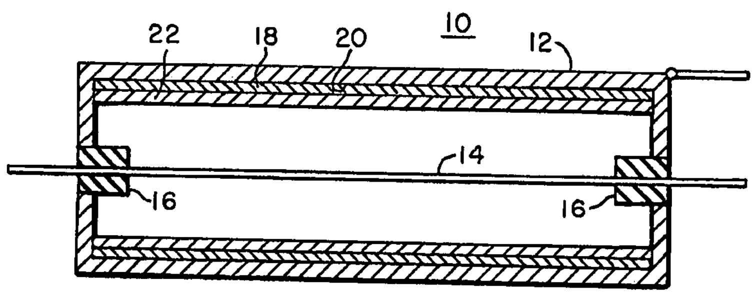


FIG. 1

LONG LIVED PROPORTIONAL COUNTER NEUTRON DETECTOR

BACKGROUND OF THE INVENTION

The present invention relates to radiation detectors and more particularly to proportional counter neutron detectors which are used in proximity to a nuclear reactor. The most widely used proportional counter neutron detector comprises an hermetically sealed member having a high neutron cross-section, neutron absorptive coating on the interior surface thereof, with a centralized electrically conductive collector electrode disposed within the sealed member. The chamber is filled with a mixture of inert gas and selected poly-atomic gases which improve the operational characteristics of the device. An incoming neutron is absorbed in the coating, and atomic particles are emitted which cause ionization of fill gas constituents producing electrons which are drawn to the collector electrode, which is connected to the recording electronic system. A widely used neutron absorptive material is boron-10 isotope, which upon neutron absorption emits charged helium and lithium particles. These particles deposit their kinetic energy in the fill gas upon traversing the fill gas. Ion pairs and electrons are produced from the fill gas, and the electrons are drawn to the positively charged collector electrode wire. With a properly designed counter and applied voltage, the electric field in the vicinity of the center wire is sufficiently high to enable the approaching electrons to make a succession of ionizing collisions, with the fill gas atoms. This avalanching or multiplication leads to the formation of a signal pulse which can be sensed by the external electronic package to register the detection of a neutron capture.

The fill gas typically used is selected to have an adequately low ionization potential, and for its characteristic of producing ion pairs from interaction with the charged particles. The noble gases fit these requirements, and argon is widely used as the noble gas material. It has been found that the signal pulse sharpness, or rate of rise of signal, is distinctly influenced by the electron drift velocity through the gas to the center wire, under the influence of the impressed electric field. The noble fill gases such as argon, offer rather low electron drift velocities. It has been the practice to add small amounts of poly-atomic molecular gases to the main noble gas fill to improve the electron drift velocity characteristic of the fill gas. Typically, the additive gas is present in an amount of about 5 volume percent of the total gas fill. This improvement in drift velocity is traceable to the ability of low-energy electrons to undergo inelastic collisions with the poly-atomic molecules.

The addition of the poly-atomic gas to the fill gas is also desired to serve as a photon absorptive constituent within the ionization chamber. Photons may be produced in the ionization chamber as a result of excitation of the noble gas constituent. Such photons can cause excessive multiplication, which will show up as background noise level in the output electronics, or produce spurious counting events. In the extreme, voltage breakdown may be produced resulting in continuous conduction and inoperativeness of the device. The poly-atomic fill gas should be selected to be highly abosrptive of photon emission, which instead of producing re-emission of photons, results in dissipation of the photon energy by the dissocition of the poly-atomic molecule. It is desirable that the dissociation products of the poly-atomic gas molecule additive have the ability to recombine after dissociation, and commonly used poly-atomic gases which meet this requirement include carbon dioxide and boron trifluoride. It has been discovered that the neutron absorptive active element disposed on the interior wall of the ionization chamber presents a target for competitive combination with the dissociated molecules. This undesired wall combination prevents the desired recombination of the decomposition products back to the recombined molecule of poly-atomic gas additive. Thus, with high accumulated neutron exposure, or even with relatively low neutron exposure, with voltage applied, the recombination property of the gas diminishes. A portion of the dissociated products combine with the neutron absorptive material on the wall rather than with the gas constituent with which it was originally present as a poly-atomic molecule. It is desirable to isolate the boron-10 neutron absorptive material which is deposited on the wall, from the dissociation products of the additive gas. The dissociated gases will be prevented from recombining with the boron-10 coating, and will recombine as the gaseous poly-atomic fill gas molecule. The provision of an isolating coating over the neutron absorptive material to prevent combination of dissociated poly-atomic fill gas constituents with the neutron absorptive coating material can result in significantly improved operating life for the device.

SUMMARY OF THE INVENTION

A proportional counter neutron detector comprises an hermetically sealed member. A high neutron cross-section, neutron absorptive coating material is provided on the interior surface of the sealed member. A generally centralized electrically conductive collector electrode is disposed within the chamber defined by the sealed member. This electrode is insulatingly brought through the sealed member for connection to a potential source and electronic recording means. A fill gas is provided within the chamber substantially comprising inert noble gas with a small portion of poly-atomic fill gas a predetermined pressure. The poly-atomic fill gas is ionizable by the radiation emitted by the neutron absorptive coating. A thin isolating film of selected metal or metal oxide, which is substantially transmissive to neutrons and to radiation products emitted by the neutron capture coating, is disposed over the neutron absorptive coating. The isolating film is substantially non-reactive with the dissociation products of the poly-atomic fill gas.

BRIEF DESCRIPTION OF THE DRAWINGS

The sole FIGURE shows the proportional neutron detector in cross-section.

DESCRIPTION OF THE PREFERRED EMBODIMENT

The proportional neutron detector **10** comprises an hermetically sealed enclosure member **12**, which is specifically cylindrical, and formed of a material such as stainless steel. The centralized collector electrode wire **14** is disposed along the longitudinal axis of the enclosure member **12**, and passes through insulated seal means **16** at opposite ends of the enclosure member **12**. The electrode wires are externally connected to the electronic recording apparatus, and the conductive

enclosure member is typically also connected thereto as the ground element. A thin coating of boron-10 neutron absorptive material **18** is disposed on the interior surface **20** of the enclosure member **12.** This neutron absorptive coating is typically deposited in an amount of about one milligram per square centimeter. The chamber defined by the enclosure member has a fill gas of inert noble gas, typically argon, and a poly-atomic constituent, typically carbon dioxide in an amount of about 5 volume percent of the total fill gas. The carbon dioxide content can be readily varied from about 2 to 20 volume percent. A thin isolating film **22** is disposed over the neutron absorptive material coating **18** to effectively isolate the neutron absorptive material from the dissociation products of the poly-atomic fill gas constituent. The isolating film **22** is preferably a metal or metal oxide which is substantially transmissive to neutrons and neutron emission products, and is substantially non-reactive with the dissociation products of the poly-atomic fill gas. The isolation film is preferably aluminum or aluminum oxide and is deposited in an amount of about 0.02 to 0.2 mg. per square centimeter. The metal or metal oxide film prevents the dissociation products of the poly-atomic fill gas from contacting the boron-10 coating. In a detector in which the poly-atomic fill gas constituent is carbon dioxide, the metal or metal oxide thin isolation film should be selected to have a low oxygen affinity.

The isolative film **22** can be deposited by a thermal evaporation or gas sputtering application process which are well known in the art. The isolation film must be thin enough so as not to absorb a substantially portion of the energy of the charged particles produced as a result of neutron absorption, since any such decrease in the kinetic energy of these particles would reduce the number of ion pairs that can be formed in the fill gas and would degrade the performance characteristic of the device. Other poly-atomic fill gases which can be used include methane and boron trifluoride.

I claim:

1. A proportional neutron detector comprising an hermetically sealed member having a high neutron cross-section, neutron absorptive coating on the interior surface thereof, and a generally centralized electrically conductive collector electrode disposed within the sealed member and insulatingly brought through the member for connection to a potential source, a fill gas of noble gas and a small portion of a poly-atomic fill gas at predetermined pressure within said sealed member which fill gas is ionizable by the radiation emitted by the neutron absorptive coating upon neutron capture, the improvement wherein a thin isolation film of selected metal or metal oxide, which is substantially transmissive to neutrons and is non-reactive with the dissociation products of the poly-atomic fill gas, is disposed over the neutron absorptive coating.

2. The proportional neutron detector specified in claim **1,** wherein the fill gas is carbon dioxide, and the metal or metal oxide thin film has a low oxygen affinity.

3. The proportional neutron detector specified in claim **1,** wherein the metal or metal oxide thin film comprises aluminum or aluminum oxide in an amount of from about 0.02 to 0.2 milligram per square centimeter.

* * * * *

US006011265A

United States Patent [19]

Sauli

[11] **Patent Number: 6,011,265**

[45] **Date of Patent: Jan. 4, 2000**

[54] **RADIATION DETECTOR OF VERY HIGH PERFORMANCE**

[75] Inventor: **Fabio Sauli**, Geneva, Switzerland

[73] Assignee: **European Organization For Nuclear Research**, Geneva, Switzerland

[21] Appl. No.: **08/956,128**

[22] Filed: **Oct. 22, 1997**

[51] **Int. Cl.**^{7} **G01T 1/185**; H01J 47/02

[52] **U.S. Cl.** **250/374**; 250/385.1

[58] **Field of Search** 250/374, 385.1

[56] **References Cited**

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J. Phys. III France 6 (1996) pp. 337–347, Mar. 1996, Title: The C.A.T. Pixel Proportional Gas Counter Detector, Author: Bartol, F., et al.

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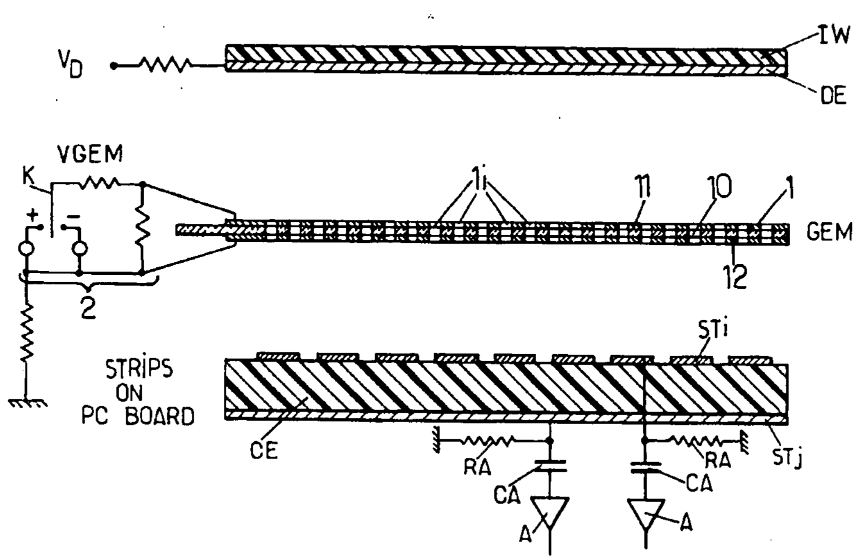
Primary Examiner—Constantine Hannaher
Assistant Examiner—Andrew Israel
Attorney, Agent, or Firm—Larson & Taylor

[57] **ABSTRACT**

A radiation detector in which primary electrons are released into a gas by ionizing radiations and drifted through an electric field to a collecting electrode for detection. It further includes a gas electron multiplier formed by one or several matrices of electric field condensing areas which are distributed within a solid surface perpendicular to the electric field. Each electric field condensing area consists of a tiny hole passing through the solid surface that forms a dipole adapted to produce a local electric field amplitude enhancement proper to generate an electron avalanche from one primary electron. The gas electron multiplier operates thus as an amplifier or a preamplifier within a host radiation detector.

26 Claims, 14 Drawing Sheets



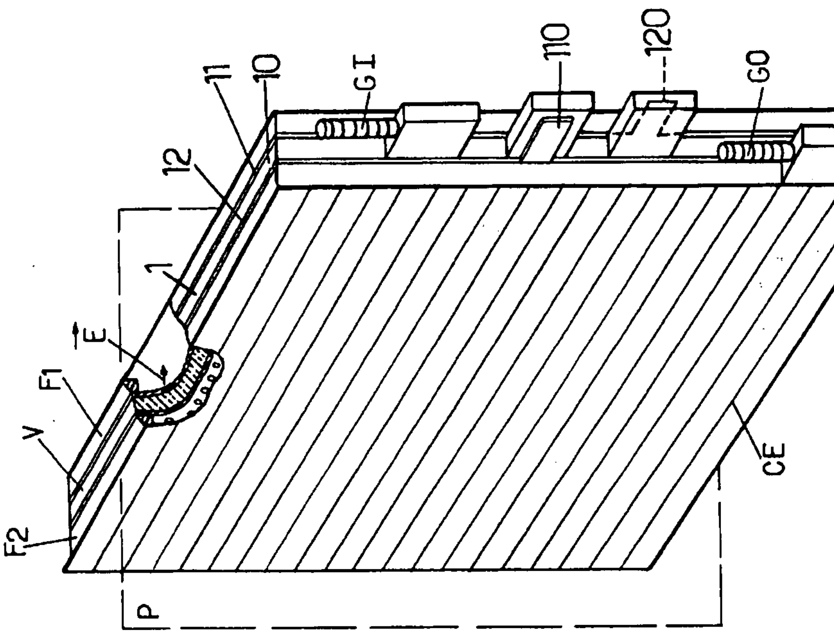

F2
V
F1
E
1
12
11
10
GI
110
120
GO
CE
P

FIG. 1b.

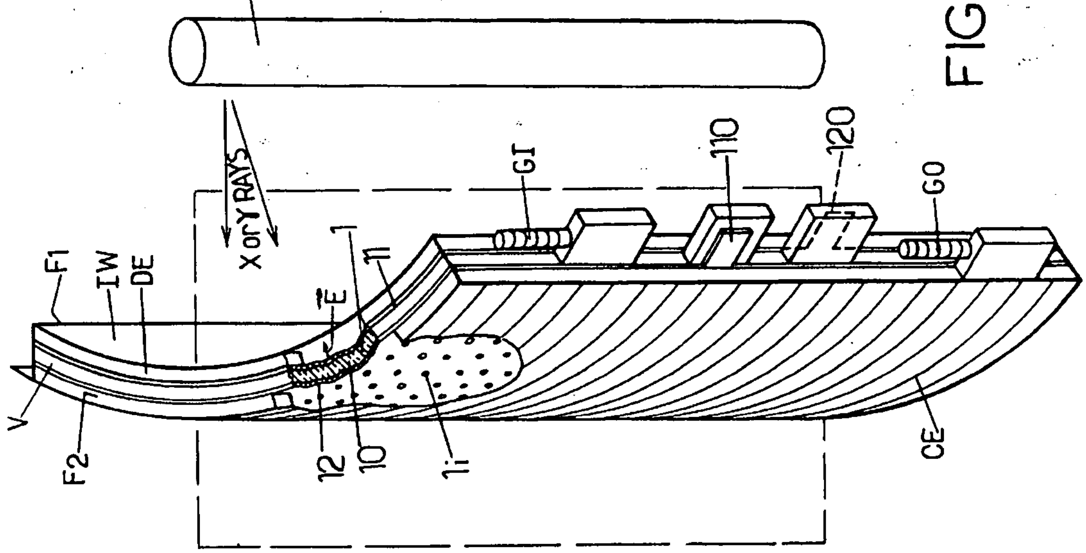

S
X or Y RAYS
F1
IW
DE
V
F2
E
1
11
12
10
1i
GI
110
120
GO
CE

FIG. 1a

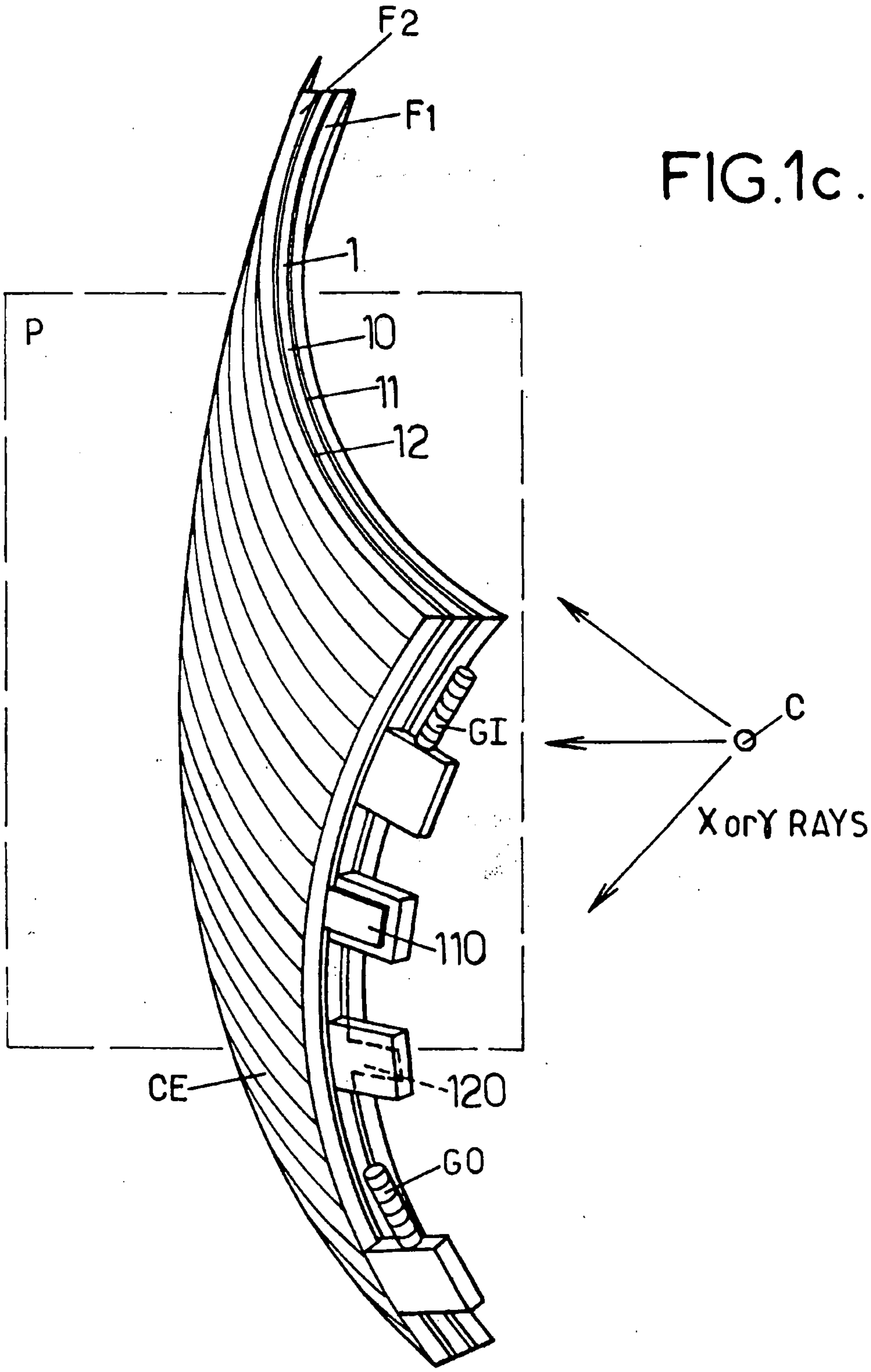
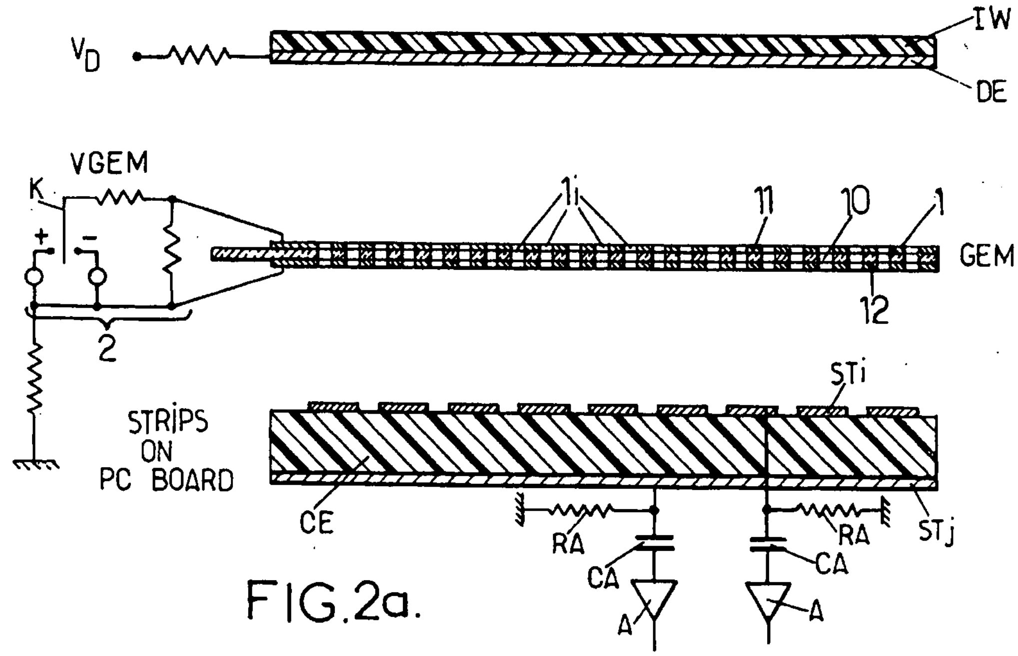
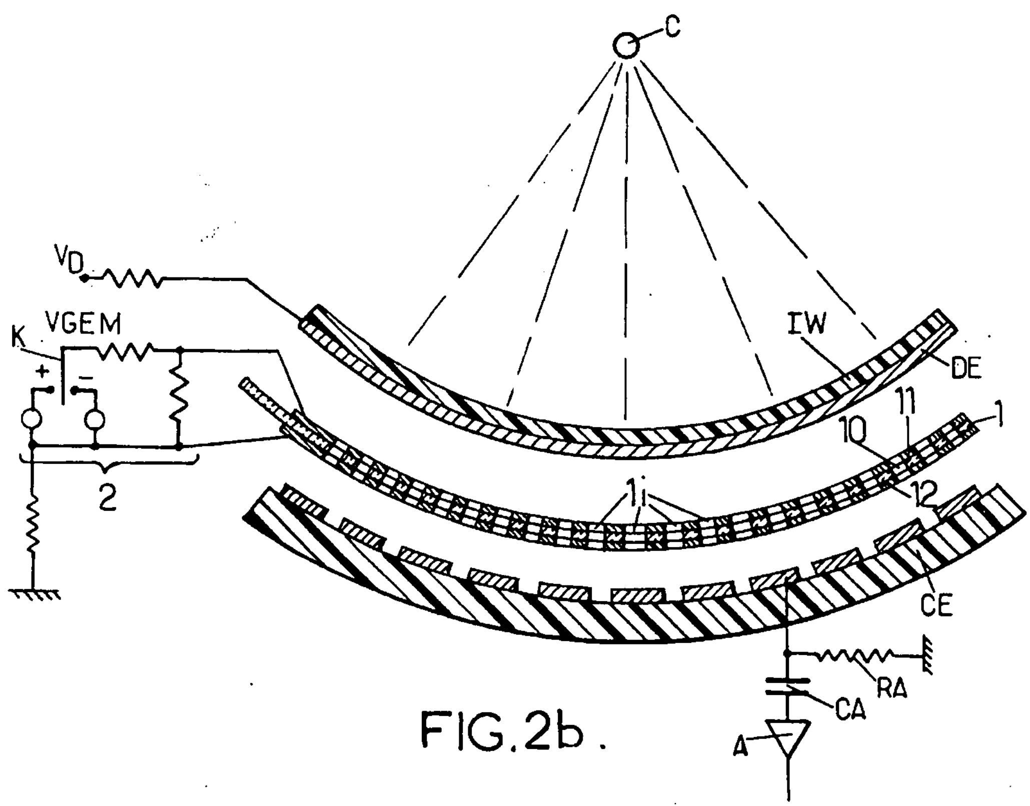


FIG.1c.



V_D
IW
DE
VGEM
K
+
-
1i
11
10
1
GEM
12
2
STi
STRIPS ON PC BOARD
CE
RA
RA
STj
CA
CA
A
A

FIG.2a.



C
V_D
VGEM
K
+
-
IW
DE
11
10
1
12
2
1i
CE
RA
CA
A

FIG.2b.

FIG.3a.

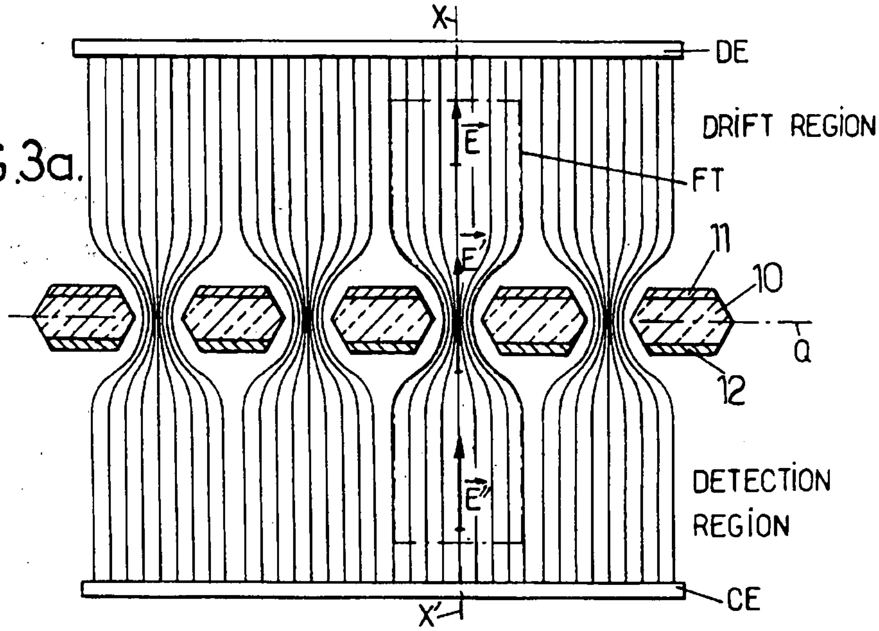
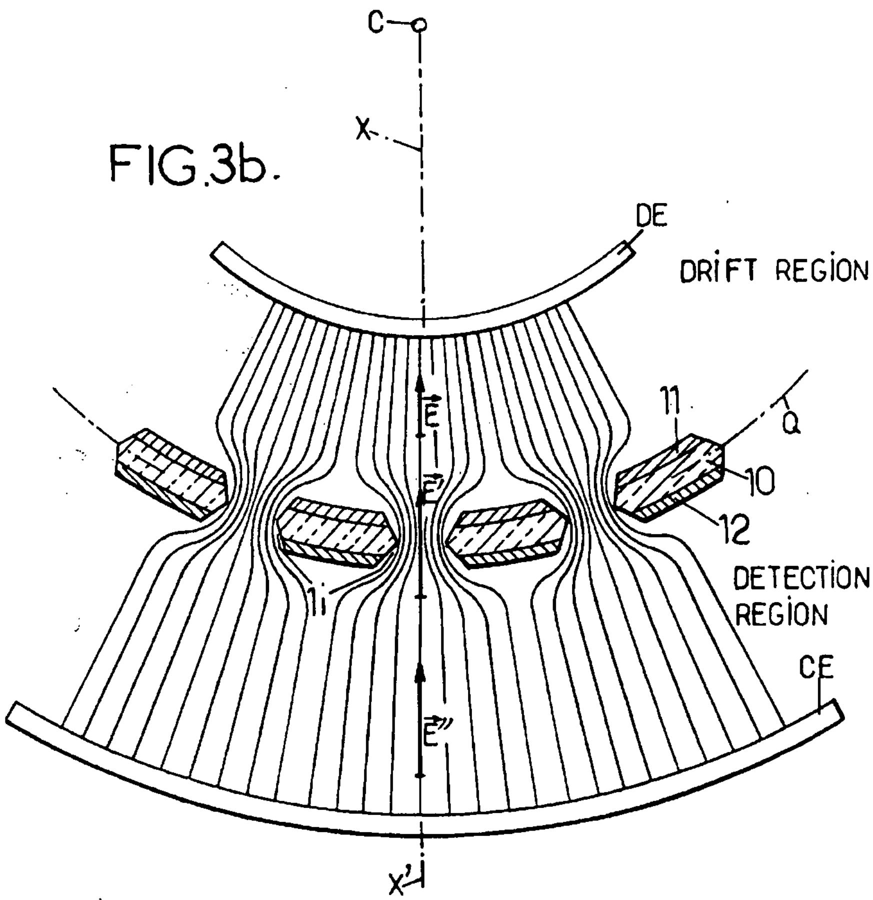

X
DE
DRIFT REGION
E
FT
E'
11
10
Q
12
DETECTION
REGION
E''
CE
X'

FIG.3b.


C
X
DE
DRIFT REGION
E
11
Q
E'
10
12
1i
DETECTION
REGION
CE
E''
X'

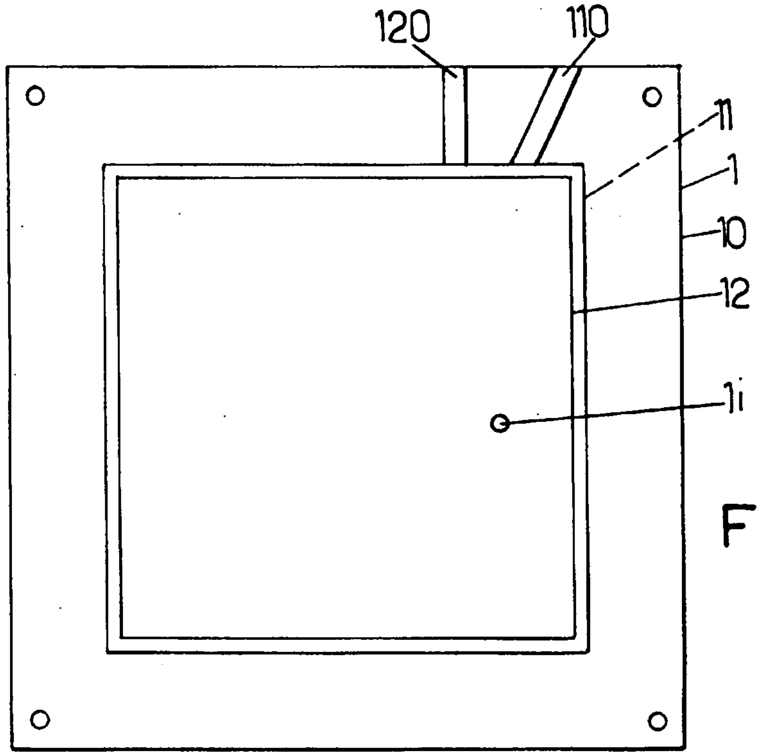


FIG.4a.

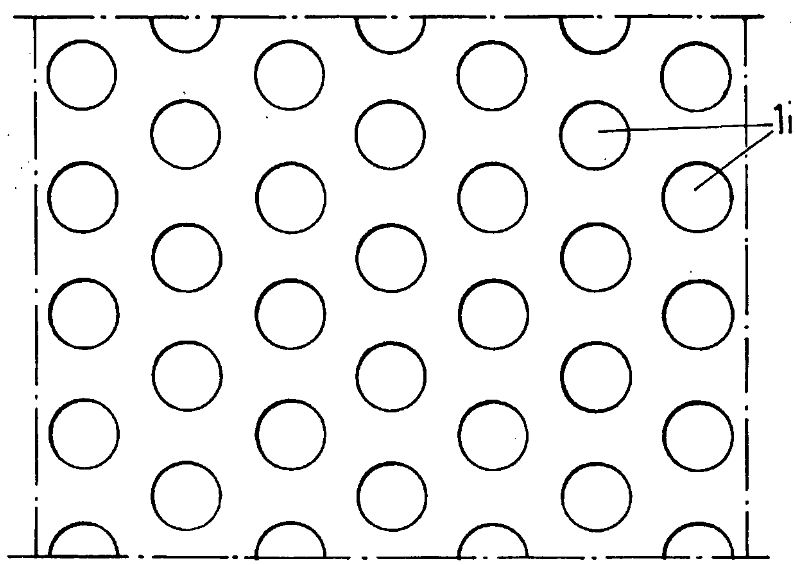


FIG.4b.

FIG.4c.

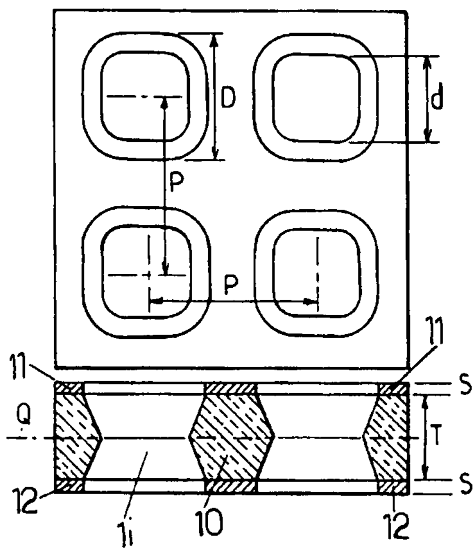


FIG.4d.

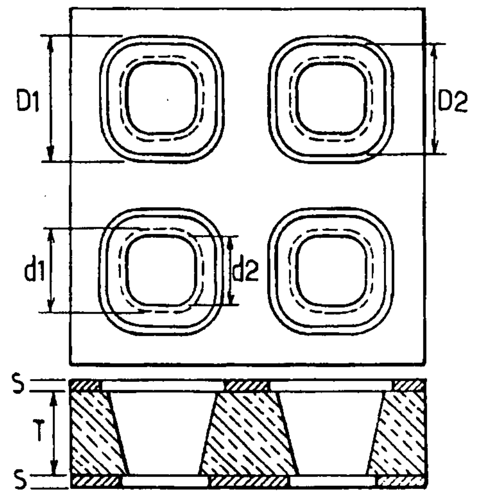


FIG.4e.

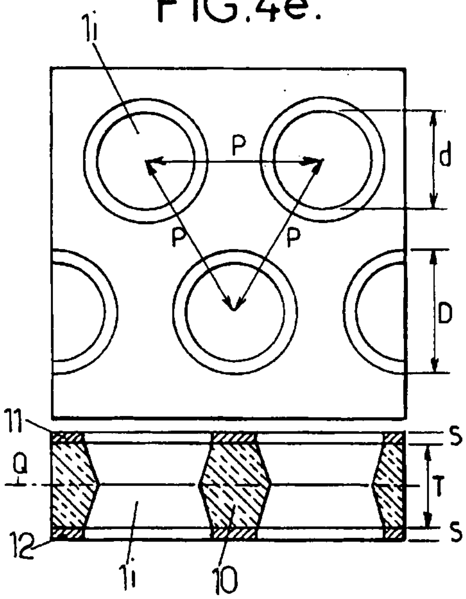


FIG.4f.

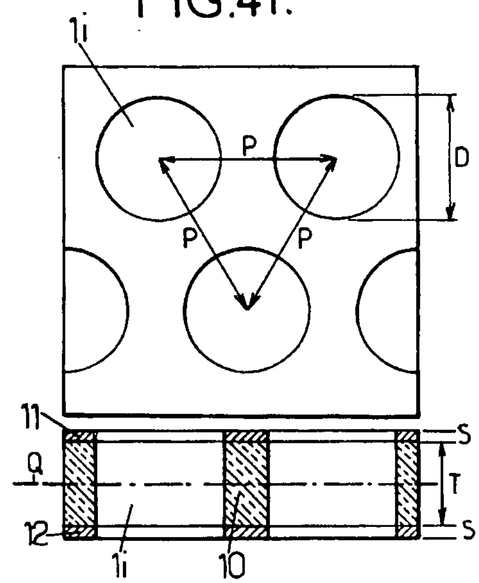


FIG.5a.

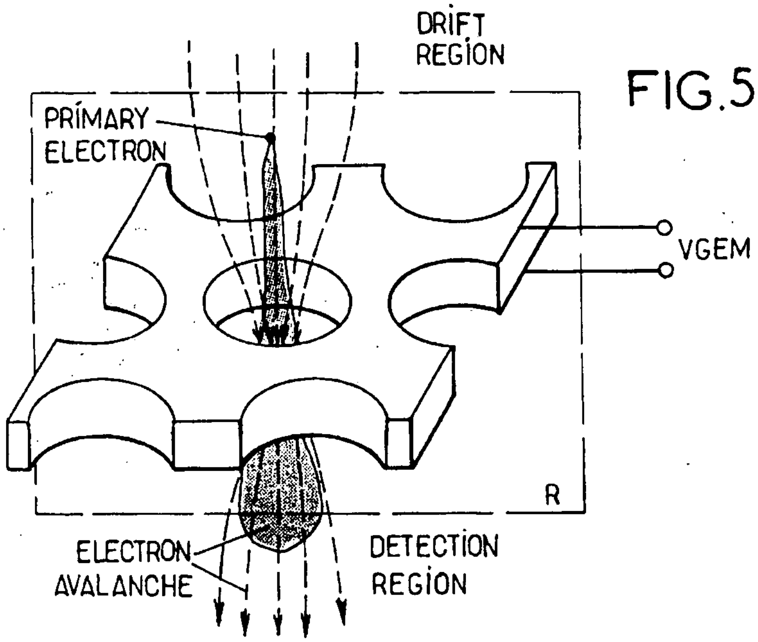
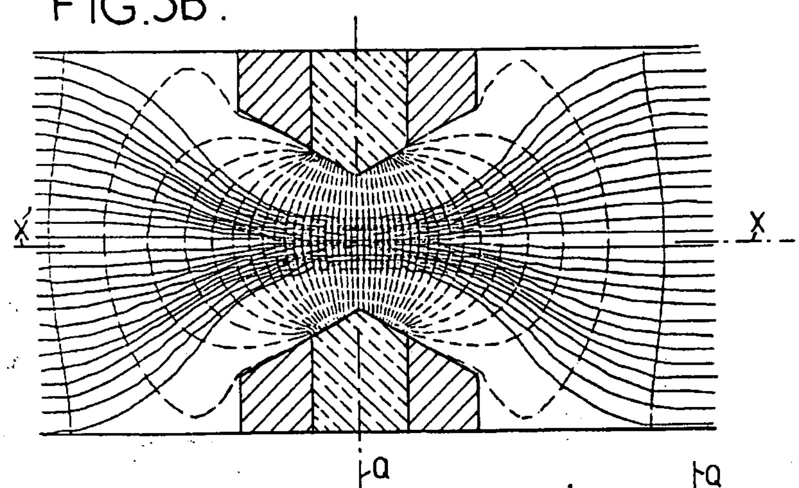


FIG.5b.



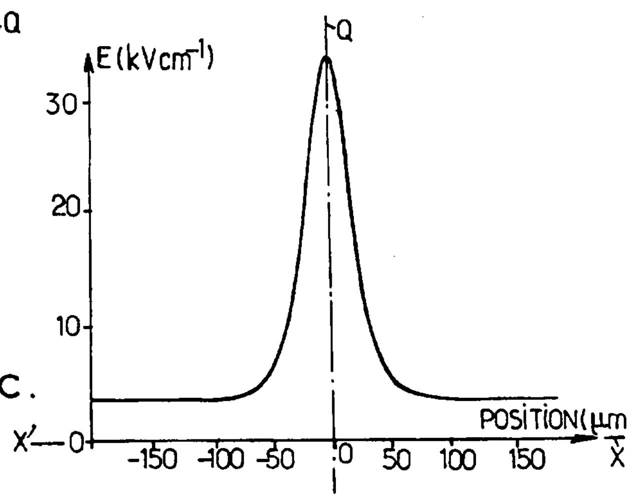


FIG.5c.

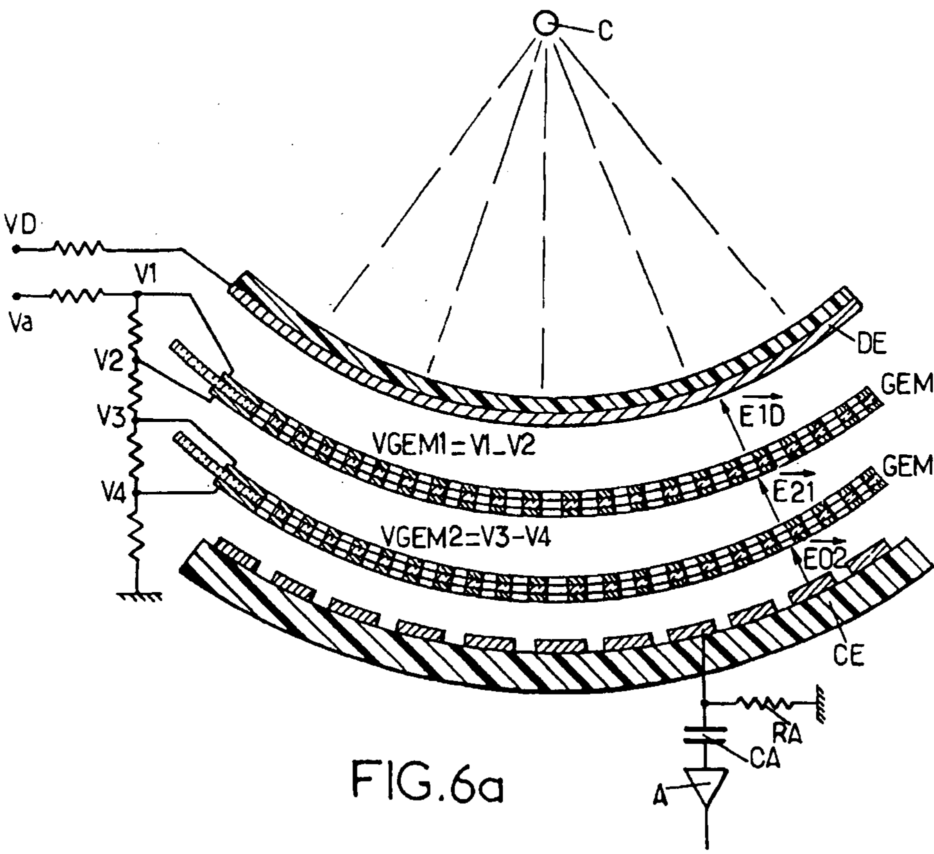

C
VD
V1
Va
V2
V3
V4
DE
GEM1
GEM2
VGEM1=V1_V2
VGEM2=V3-V4
E1D
E21
E02
CE
RA
CA
A

FIG.6a

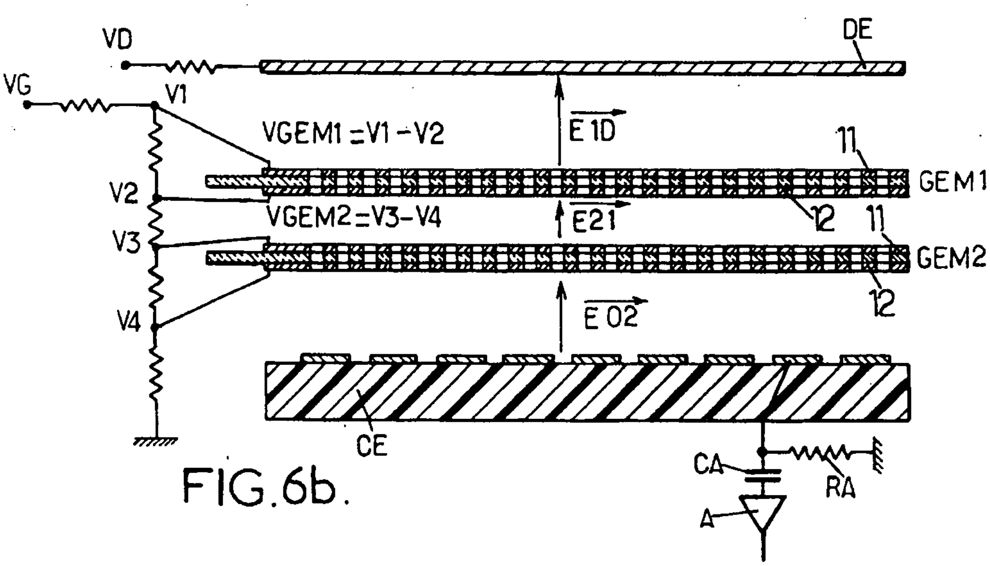

VD
DE
VG
V1
VGEM1=V1-V2
E1D
11
GEM1
V2
VGEM2=V3-V4
E21
12
11
V3
GEM2
12
V4
E02
CE
CA
RA
A

FIG.6b.

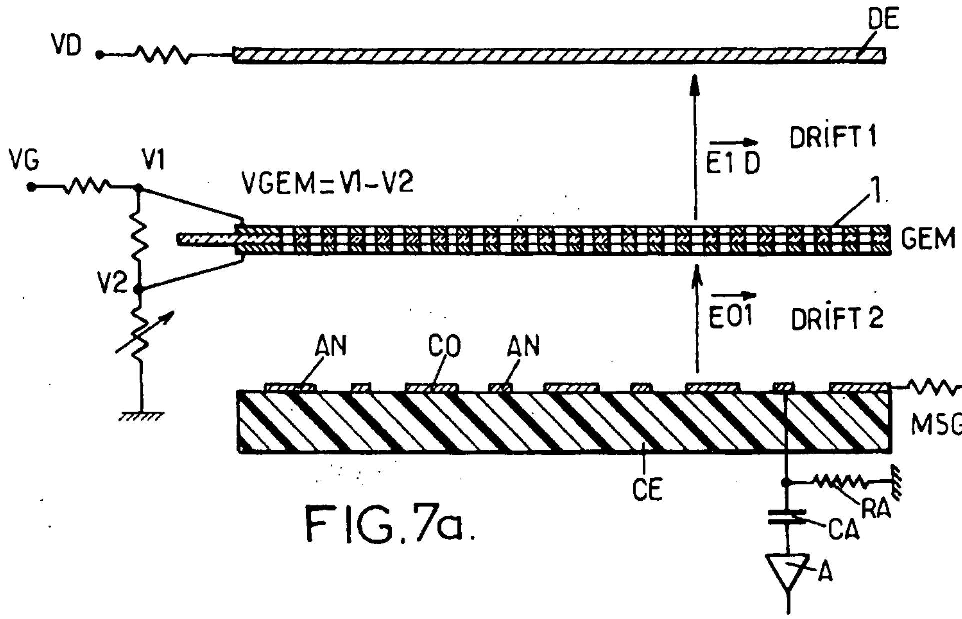

VD
DE
VG
V1
VGEM=V1-V2
E1D
DRIFT 1
1
GEM
V2
E01
DRIFT 2
AN
CO
AN
VC
MSGC
CE
RA
CA
A

FIG.7a.

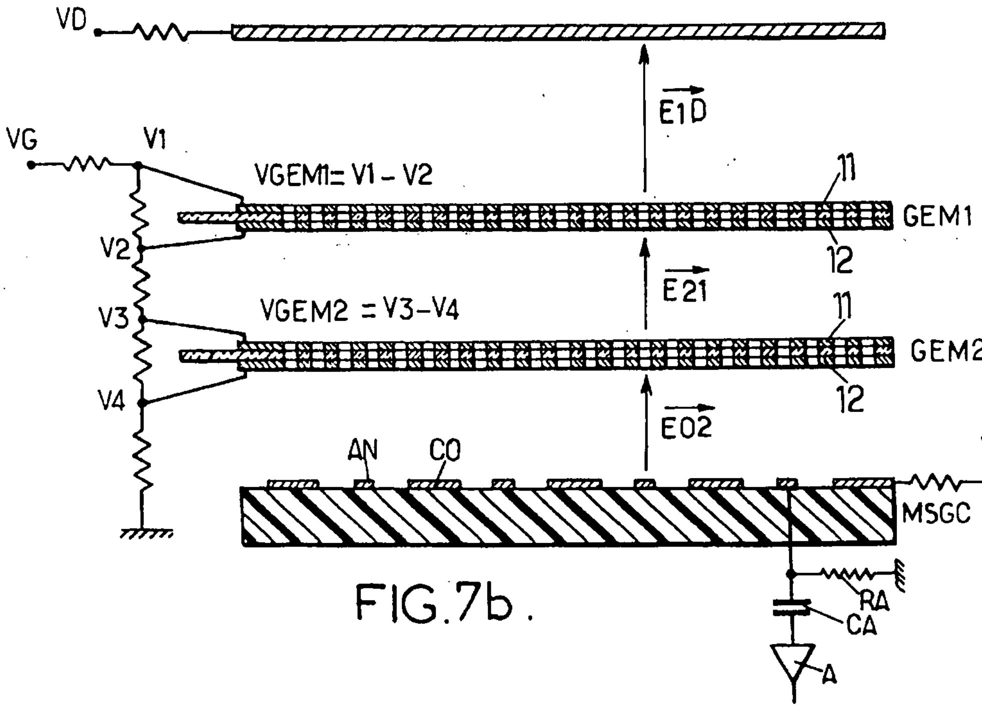

VD
E1D
VG
V1
VGEM1=V1-V2
11
GEM1
V2
12
E21
V3
VGEM2 =V3-V4
11
GEM2
V4
12
E02
AN
CO
VC
MSGC
RA
CA
A

FIG.7b.

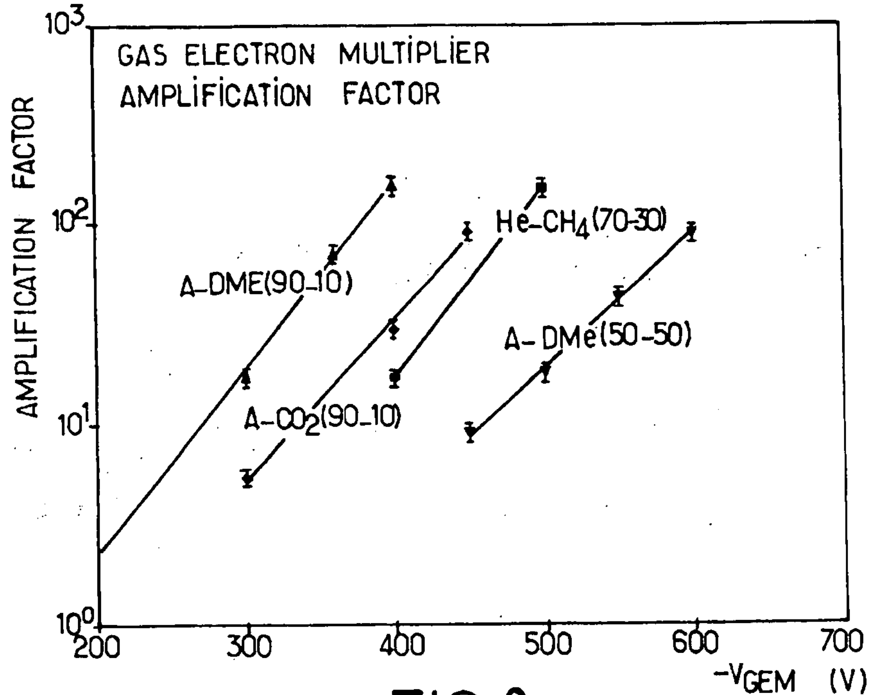

GAS ELECTRON MULTIPLIER
AMPLIFICATION FACTOR
AMPLIFICATION FACTOR
10^3
10^2
10^1
10^0
A-DME(90-10)
He-CH_4(70-30)
A-DME(50-50)
A-CO_2(90-10)
200
300
400
500
600
700
$-V_{GEM}$ (V)

FIG. 8a.

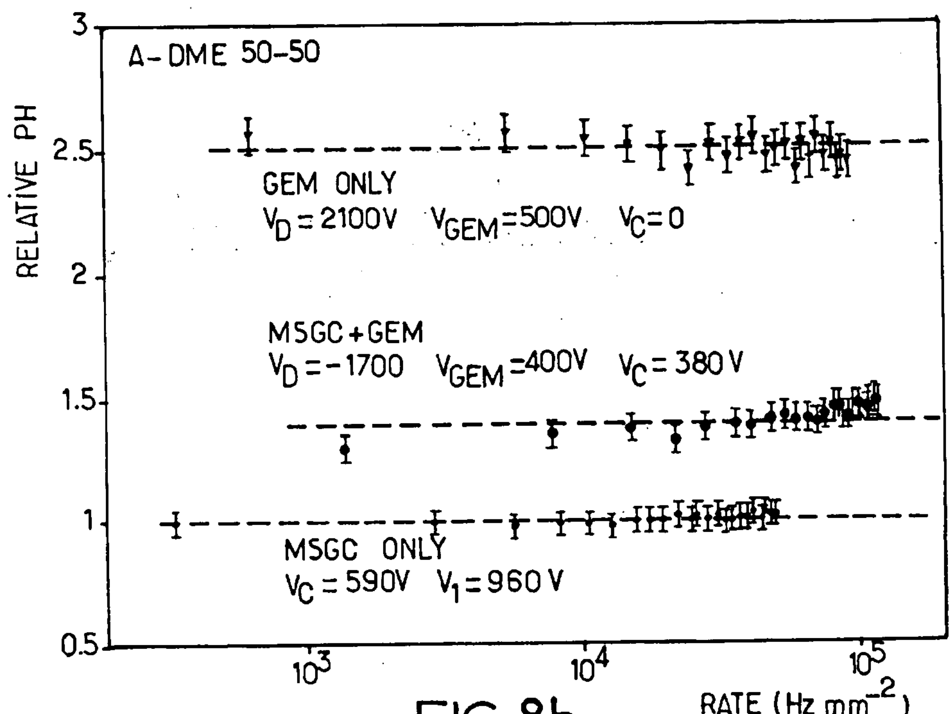

A-DME 50-50
RELATIVE PH
3
2.5
2
1.5
1
0.5
GEM ONLY
$V_D = 2100V$ $V_{GEM} = 500V$ $V_C = 0$
MSGC+GEM
$V_D = -1700$ $V_{GEM} = 400V$ $V_C = 380V$
MSGC ONLY
$V_C = 590V$ $V_1 = 960V$
10^3
10^4
10^5
RATE (Hz mm^{-2})

FIG. 8b.

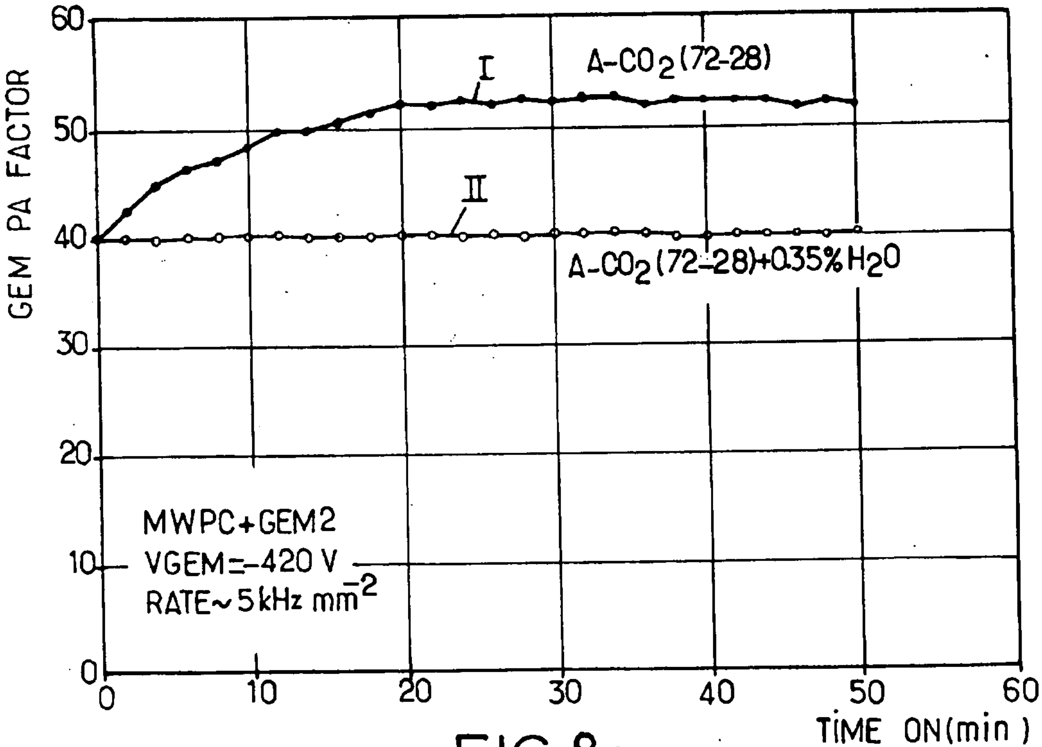

GEM PA FACTOR
60
50
40
30
20
10
0
I
A-CO_2 (72-28)
II
A-CO_2 (72-28)+0.35% H_2O
MWPC+GEM2
VGEM=-420 V
RATE~5 kHz mm^{-2}
0 10 20 30 40 50 60
TIME ON(min)

FIG. 8c.

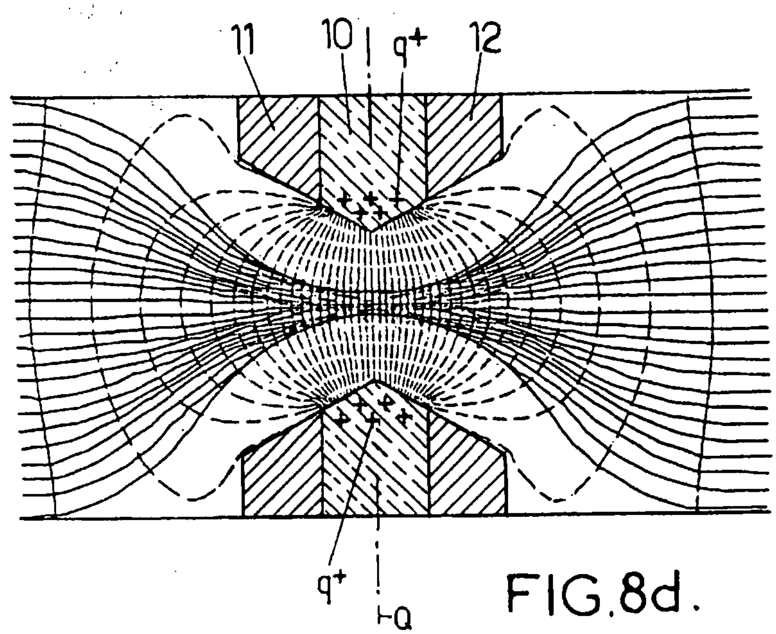

11
10
q^+
12
q^+
-Q

FIG. 8d.

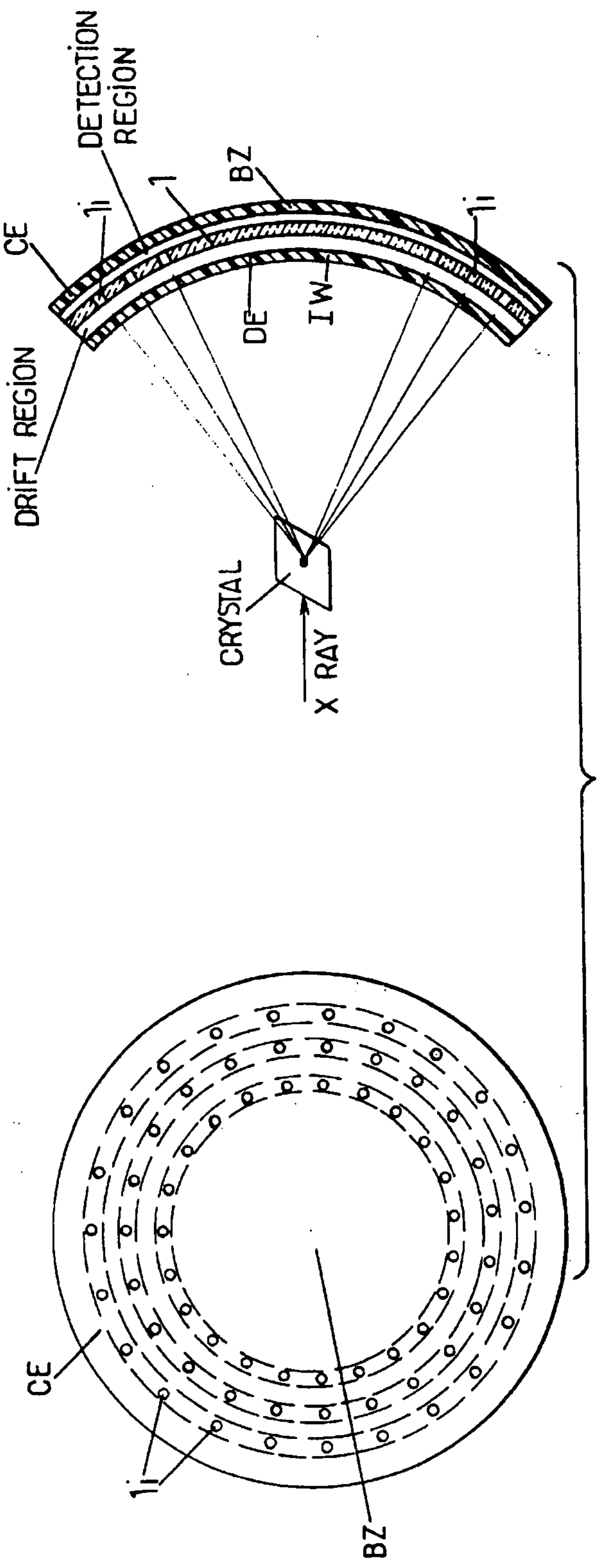
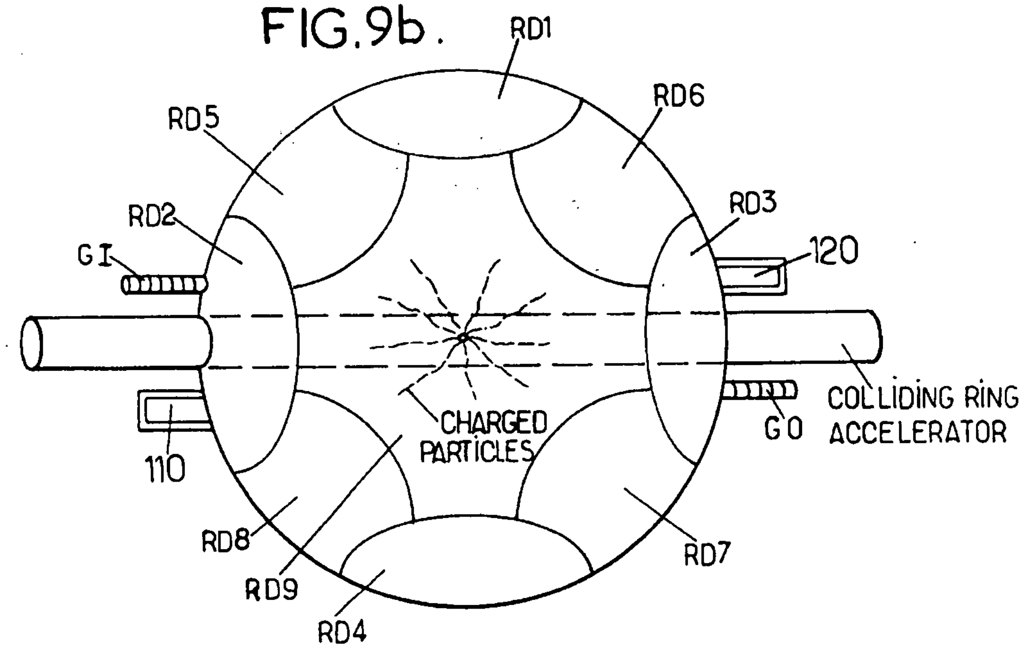

DETECTION REGION
CE
1i
1
BZ
1i
DE
IW
DRIFT REGION
CRYSTAL
X RAY
CE
1i
BZ

FIG.9a.

FIG.9b.


RD1
RD6
RD5
RD3
RD2
120
GI
CHARGED PARTICLES
COLLIDING RING ACCELERATOR
GO
110
RD8
RD7
RD9
RD4

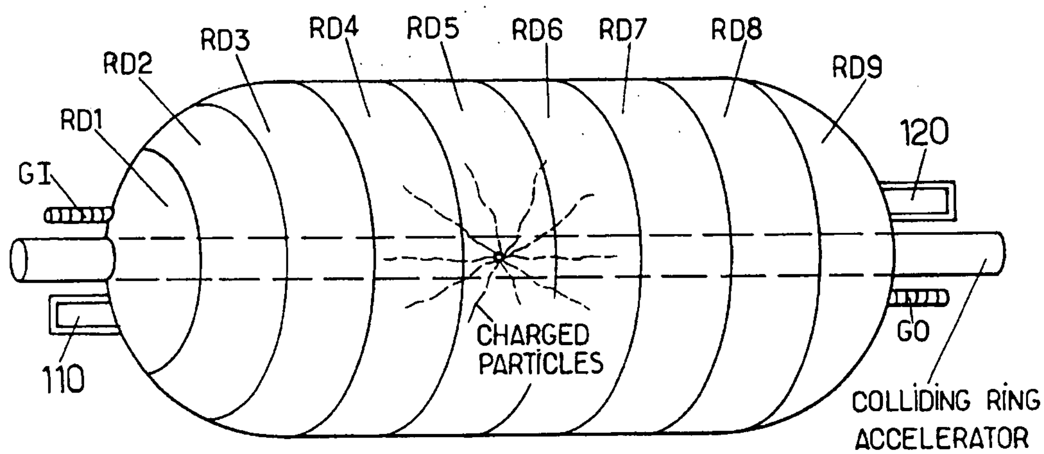

RD4
RD5
RD6
RD7
RD8
RD3
RD2
RD9
RD1
120
GI
CHARGED PARTICLES
GO
110
COLLIDING RING ACCELERATOR

FIG.9c.

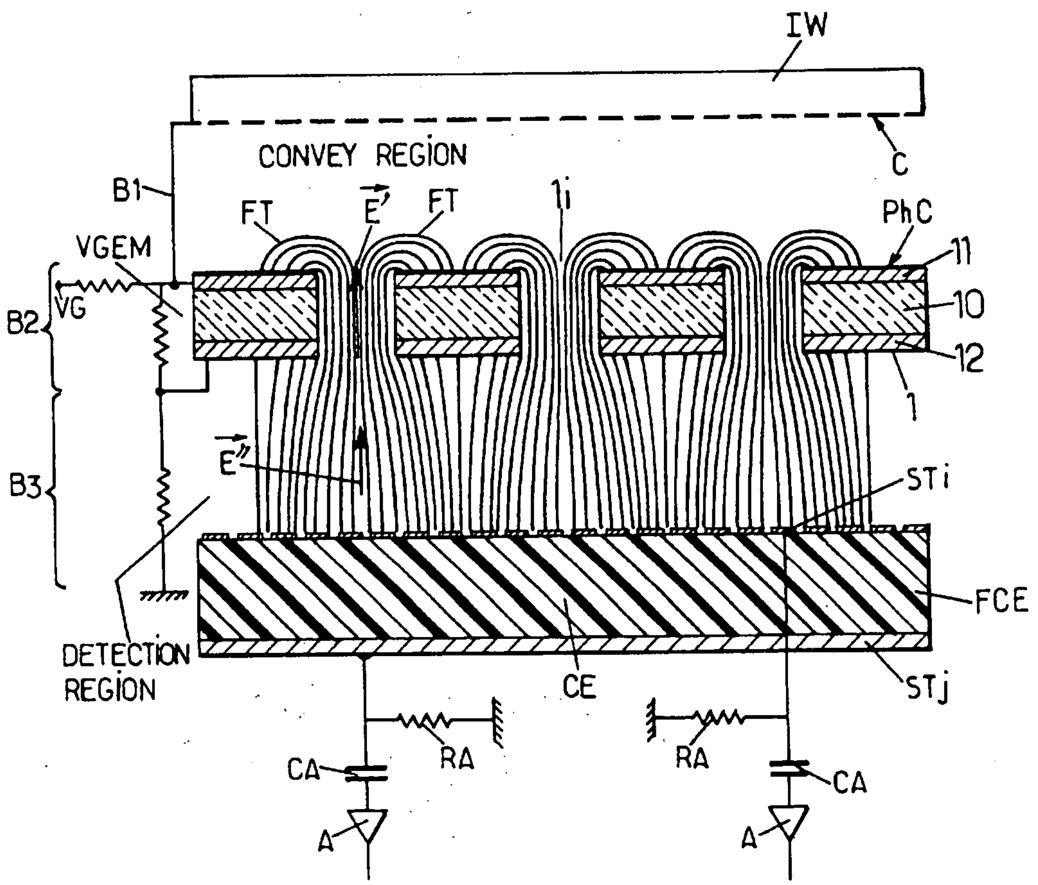

IW
C
CONVEY REGION
B1
FT
E'
FT
1i
PhC
11
10
12
1
VGEM
VG
B2
B3
E''
STi
FCE
DETECTION REGION
CE
STj
RA
RA
CA
CA
A
A

FIG.10.

RADIATION DETECTOR OF VERY HIGH PERFORMANCE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to an improved technique for embodying a radiation detector of very high performance that can be used for detecting in position ionizing radiations such as charged particles, photons, X-rays and neutrons.

2. Brief Description of the Prior Art

Radiation detectors exploiting the process of ionization and charge multiplication in gases have been in use with continued improvements since hundred years. Methods for obtaining large "stable" proportional gains in gaseous detectors are a continuing subject of investigation in the detectors community.

Several years ago, G. CHARPAK and F. SAULI introduced the multistep chamber, thereafter designated as MSC, as a way to overcome on limitations of gain in parallel plate and multiwire proportional chambers, thereafter designated as MWPC.

In MSC chambers, two parallel grid electrodes mounted in the drift region of a conventional gas detector and operated as parallel plate multipliers allow to preamplify drifting electrons and transfer them into the main detection element. Operated with a photosensitive gas mixture, the MSC chamber allows to reach gains large enough for single photodetection in ring-imaging CHERENKOV detectors, thereafter designated as RICH. For more details with respect to MSC chambers and RICH chambers, we refer to the following publications:

G. CHARPAK and F. SAULI, Physics Letters, vol.78B, 1978, p.523, and

M. ADAMS and al., Nuclear Instrumentation Methods, 217, 1983, 237.

More recently, G. CHARPAK and Y. GIOMATARIS have developed an improved radiation detector device thereafter designated as MICROMEGAS which is a high gain gas detector using as multiplying element a narrow gap parallel plate avalanche chamber.

In a general point of view, such a detector consists of a gap in the range 50 to 100 μm which is realized by stretching a thin metal micromesh electrode parallel to a read-out plane. G. CHARPAK and Y. GIOMATARIS have demonstrated very high gain and rate capabilities which are understood to result from the special properties of electrode avalanches in very high electric fields. For more details concerning the MICROMEGAS detector, we refer to the publication edited by Y. GIOMATARIS, P. REBOUGEARD, J. P. ROBERT and G. CHARPAK in Nuclear Instruments Methods, A376, 1996, 29.

The major point of inconvenience of both described detectors lies in the necessity of stretching and maintaining parallel meshes with very good accuracy. The presence of strong electrostatic attraction forces adds to the problem particularly for large size of the detectors. To overcome this drawback, heavy support frames are required and in the case of the MICROMEGAS detector the introduction in the gap of closely spaced insulating lines or pins with the ensuing complication of assembly and loss of efficiency is necessary.

Another radiation detector device was recently developed and proposed by F. BARTOL and al. Journal of Physics III 6 (1996), 337.

This detector device, thereafter designated as CAT, for Compteur à trous, substantially consists of a matrix of holes

which are drilled through a cathode foil. The insertion of an insulating sheet between cathode and buried anodes allows thus to guaranty a good gap uniformity and to obtain high gains.

OBJECTS OF THE INVENTION

An object of the present invention is therefore to provide a radiation detector of very high performance that overcomes the above-mentioned drawbacks of the radiation detectors of the prior art.

Another object of the present invention is furthermore to provide a radiation detector of very high performance that appears to hold both the simplicity of the MSC chamber and the high field advantages of the MICROMEGAS and CAT radiation detectors however mechanically much simpler to implement and more versatile in use.

Another object of the present invention is therefore to provide a radiation detector of very high performance in which a very high degree of accuracy and resolution is obtained thanks to an electric charges transfer coefficient which substantially equals unity.

Another object of the present invention is therefore to provide a radiation detector with substantially constant amplifying factor for counting rates up to 10^5 Hz/mm^2.

SUMMARY OF THE INVENTION

More particularly, in accordance with the present invention, there is provided a radiation detector in which primary electrons are released into a gas by ionizing radiations and drift to a collecting electrode by means of an electric field. The radiation detector of the invention includes a gas electron multiplier comprising at least one matrix of electric field condensing areas with these electric field condensing areas being distributed within a solid surface which is substantially perpendicular to the electric field. Each of the electric field condensing areas is adapted to produce a local electric field amplitude enhancement proper to generate in the gas an electron avalanche from each one of the primary electrons. The gas electron multiplier operates thus as an amplifier of given gain for the primary electrons.

The objects, advantages and other particular features of the present invention will become more apparent upon reading of the following non-restrictive description of preferred embodiments thereof which are given by way of example only with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In the appended drawings:

FIG. 1*a* is a perspective view of a preferred embodiment of a radiation detector in accordance with the present invention which is cylindrical in shape;

FIG. 1*b* is a perspective view of a particular embodiment of a radiation detector in accordance with the present invention which is planar in shape;

FIG. 1*c* is a perspective view of a particular embodiment of a radiation detector in accordance with the present invention which is spherical in shape;

FIG. 2*a* is a cross-section view along a section plane designated as plane P which is represented in phantom line for FIGS. 1*a* and 1*b*;

FIG. 2*b* is a cross-section view along a section plane designated as plane P which is represented in phantom line at FIG. 1*c*;

FIG. 3*a* is a diagram representing the electric field lines for FIG. 2*a;*

FIG. 3*b* is a diagram representing the electric field lines for FIG. 2*b;*

FIG. 4*a* is a front view representing a detail of FIG. 1*b*, such a detail consisting of a gas electron multiplier comprising one matrix of electric field condensing areas;

FIG. 4*b* is a front view of a detail of FIG. 4*a* in which the matrix of electric field condensing areas is shown in a non-limitative way to consist of circular bored-through holes;

FIGS. 4*c*, 4*d*, 4*e* and 4*f* show particular embodiments of matrices provided with bored-through holes of different shapes and pitch;

FIG. 5*a* is a perspective view of a detail of FIG. 4*b* in which the mode of operation of the gas electron multiplier in a radiation detector in accordance with the invention operates to generate an electron avalanche from a primary electron;

FIG. 5*b* is a cross-section view along a section plane designating as plane R represented in phantom line at FIG. 5*a*, in which the electric field lines and electric potential lines are represented at the level of a local electric field condensing area with the potential lines being represented in solid lines and the electric field line being represented in phantom lines;

FIG. 5*c* is a diagram representing the electric field distribution within the local condensing area shown at FIG. 5*b*, the electric field being plotted with reference to a symmetry axis X'X shown at FIG. 5*b;*

FIGS. 6*a* and 6*b* are each a schematic view of a radiation detector in accordance with the invention in which more than one matrix of electric field condensing areas are used so as to embody such a radiation detector;

FIG. 7*a* is a schematic view of a gas electron multiplier in accordance with the present invention which is inserted into a particular radiation detector, the gas electron multiplier of the invention operating thus as a preamplifier for primary electrons;

FIG. 7*b* is a schematic view representing successive gas electron multiplier in accordance with the present invention which are integrated within a particular host radiation detector, the successive gas electron multipliers operating thus as separate preamplifiers for the primary electrons;

FIG. 8*a* is a diagram representing the amplification factor which is obtained for several gas mixtures filling a radiation detector in accordance with the invention, with this amplification factor being plotted with respect to the voltage potential which is applied to a matrix of local electric field condensing areas;

FIG. 8*b* is a diagram representing the relative pulse height obtained from a radiation detector in accordance with the invention which is formed from a MSGC chamber in which a gas electron multiplier is inserted as shown at FIG. 7*a* with the relative pulse height being plotted with respect to the count-rate expressed in Hz/mm^2;

FIG. 8*c* is a diagram of comparative measures of the preamplifying or amplifying factor of a gas electron multiplier in accordance with the invention in case dry mixture of argon and carbon dioxide and a wet mixture of the latter is used as a gas filling the radiation detector in accordance with the invention, with the amplifying or preamplifying factor being plotted with respect to time expressed in minutes;

FIG. 8*d* is a preferred embodiment for one local electric field condensing area in which enhancement of the electric field along the central axis of symmetry of this local electric field condensing area is furthermore increased thanks to permanent electric charges which are implanted into particular zones of this local electric field condensing area;

FIG. 9*a* is a front view of a radiation detector in accordance with the present invention which is particularly adapted to be used for crystallography experiments;

FIGS. 9*b* and 9*c* are front views representing a preferred embodiment of a radiation detector in accordance with the present invention which is more particularly adapted for the detection of ionizing radiations which are generated by colliding particles accelerated within the colliding ring path of an accelerator of the synchrotron-type, this accelerated particles having thus very high energy levels;

FIG. 10 is a cross-section view like FIG. 3*a*, of a non limitative embodiment of the radiation detector of the invention which is more particularly directed to photons detection.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The radiation detector according to the invention is now disclosed as a non-limitative example in the present specification. Particularly, it should be kept in mind that the radiation detector in accordance with the invention can be used with the same advantages in many types of applications such as radiography, imaging medicine, and in a more general sense any kind of radiation which comes to effect to release primary electrons in a gas.

The radiation detector in accordance with the invention is thus disclosed with reference to FIGS. 1*a*, 1*b* and 1*c*.

In the accompanying drawings, the same references designate the same elements while relative dimensions of these elements are not represented for the sake of better comprehension of the whole.

As shown at FIG. 1*a*, the radiation detector in accordance to the invention is a detector of the type in which primary electrons are released into a gas by ionizing radiations with these primary electrons being drifted to a collecting electrode by means of an electric field. In the above-mentioned figures, vector $\vec{E}$ designates the electric field, CE designates the collecting electrode.

Generally, the radiation detector of the invention may comprise a vessel referred to as V containing the gas in which the primary electrons are released by an incident ionizing radiation. In FIGS. 1*a*, 1*b* and 1*c*, the ionizing radiation is designated as X-rays or gamma-rays which are generated from a source referred to as S. The X-rays or gamma-rays generated by the source S enter thus the radiation detector of the invention through an inlet window referred to as IW and generate primary electrons which are released into the gas contained within the vessel V. The inlet window IW has a metal clad inner surface generally consisting of a thin metal film which, in operation, is put at a drift potential thereafter designated as VD. As shown at FIG. 1*a* for example, the collecting electrode CE, and the inlet window IW and drift electrode DE may well form the vessel V so as to contain the gas in which the primary electrons are thus released on inpingement of the ionizing radiation. Light frames referred to as F_1, F_2 may be used to build up the vessel V.

As further shown at FIGS. 1*a*, 1*b* or 1*c*, the vessel V is further provided with a gas inlet thereafter designated as GI, and a gas outlet designated as GO, both consisting of a threaded tiny tube allowing the filling of the vessel V with

a particular gas mixture or dedicated gas as it will be disclosed in more details later in the description. Gas inlet GI and gas outlet GO may well be located onto opposite sides of the vessel V so as to insure proper gas filling and circulation.

As clearly shown at FIGS. **1***a*, **1***b* and **1***c*, the radiation detector in accordance with the invention further includes a gas electron multiplier, thereafter designated as GEM and bearing reference sign **1**, this gas electron multiplier **1** comprising at least one matrix of electric field condensing areas with these electric field condensing areas being each designated as 1_i.

In the above-mentioned figures, the electric field condensing areas are distributed within a solid surface which is substantially perpendicular to the electric field vector $\vec{E}$. Each of the electric field condensing areas 1_i is adapted to produce a local electric field amplitude enhancement which is proper to generate in the gas an electron avalanche from each one of the primary electrons. The gas electron multiplier **1** operates thus as an amplifier of given gain for these primary electrons while the collecting electrode CE allows a detection of the electron avalanche to be performed, as it is disclosed later in the specification. As shown at FIGS. **1***a*, **1***b* and **1***c*, the solid surface forming the matrix of electric field condensing areas may well have different shapes with the shape of the vessel V containing the gas being adapted accordingly as shown in the above-mentioned figures. Thus, at FIG. **1***a*, the solid surface embodying the gas electron multiplier is cylindrical in shape with both the inlet window IW and associated drift electrode DE together with collecting electrode CE being of same cylindrical shape so as to develop a radial electric field vector $\vec{E}$ which is substantially perpendicular to this cylindrical solid surface forming the gas electron multiplier **1**.

At FIGS, **1***b*, to the contrary to FIG. **1***a*, the gas electron multiplier is formed by a solid surface which is planar in shape with the inlet window IW and its associated drift electrode DE together with collecting electrode CE being parallel to one another so as to form a planar structure. As a consequence, the electric field vector, vector $\vec{E}$ which is developed between collecting electrode CE and inlet window and drift electrode DE, is substantially perpendicular to the planar solid surface embodying the gas electron multiplier **1**.

At FIG. **1***c*, the solid surface embodying the gas electron multiplier **1** is spherical in shape with this solid surface being delimited by planar intersections of this solid surface. In the same way as to FIGS. **1***a* and **1***b*, collecting electrode CE and inlet window IW and its associated drift electrode DE are spherical in shape so as to develop an electric field vector $\vec{E}$ which is substantially perpendicular to corresponding spherical solid surface embodying the gas electron multiplier **1**.

As shown at FIGS. **1***a*, **1***b* and **1***c*, each electric field condensing area 1_i is represented for better comprehension as to consist of a hole in which the local electric field amplitude enhancement generated thereto is substantially symmetrical in relation to an axis of symmetry of this condensing local area. This local electric field amplitude enhancement is thus substantially at a maximum at the center of symmetry of each condensing local area 1_i. In accordance with one particular aspect of the radiation detector of the invention, the electric field condensing areas 1_i are substantially identical in shape and regularly distributed within the solid surface whichever its shape as shown at FIGS. **1***a* to **1***c* so as to form the gas electron multiplier **1**.

More details relative to the structure and the mode of operation of the gas electron multiplier **1** embodying the radiation detector of the invention will be given now with reference to FIGS. **2***a*, **2***b* and **3***a*, **3***b*.

FIG. **2***a* represents a cross-section view of the radiation detector in accordance with the invention as shown at FIG. **1***a* or FIG. **1***b* with this cross-section view being taken along intersecting plane P which is shown in phantom line at FIGS. **1***a* and **1***b* while FIG. **2***b* is a cross-section view along corresponding intersecting plane P shown in phantom line at FIG. **1***c*.

FIGS. **2***a* and **2***b* differ only in the extent that the same elements of FIG. **2***b* are bent owing to the spherical shape of the solid surface embodying the gas electron multiplier **1** and the collecting electrode CE, the inlet window IW and its associated drift electrode DE. In any case, collecting electrode CE is deemed to consist as an example of metal pads or strips which are laid onto a printed circuit board so as to allow detection of the electrode avalanches as previously mentioned in the specification.

As shown at FIGS. **2***a* and **2***b* in a preferred embodiment of the gas electron mutiplier forming the radiation detector of the invention, the matrix of electric field condensing areas 1_i may comprise a foil metal clad insulator, referred to as **10**, on each of its faces so as to form a first and second metal-cladding, referred to as **11** and **12** respectively, with these metal-cladding sandwiching the insulator foil **10** to form a regular sandwich structure. The matrix of electric field condensing areas further comprises a plurality of bored-through holes, or through holes referred to as 1_i, traversing the regular sandwich structure as shown at FIGS. **2***a* and **2***b* so as to form these electric field condensing areas.

In addition, biasing means are adapted to develop a bias voltage potential which is applied to the first and second metal cladding **11**, **12**, so as to generate at the level of each of the bored-through holes one electric field condensing area 1_i. At FIGS. **2***a* and **2***b*, the biasing means are indicted at **2** and adaptated to develop a difference potential denoted VGEM.

The mode of operation of the radiation detector in accordance with the invention and more particularly the mode of operation of the gas multiplier **1** which is shown at FIGS. **2***a* and **2***b* is now disclosed with reference to FIG. **3***a* and FIG. **3***b*.

Generally speaking, with the regular sandwich structure being put in operation substantially perpendicular to the electric field vector $\vec{E}$, the first metal-cladding **11** forms thus an input face for the drift electrons while the second metal-cladding **12** forms an output face for any electron avalanche which is generated at the level of each bored-through hole forming one of the electric field condensing areas 1_i.

With reference to FIG. **3***a*, the electric field lines bearing the electric field vector $\vec{E}$ are represented between drift electrode DE and the gas electron multiplier **1**, respectively the latter and collecting electrode CE while the electric field lines bearing the electric field vector $\vec{E}''$ are represented between the gas electron multiplier **1** and the collecting electrode CE. With the first **11** and second **12** metal-cladding being put at a convenient voltage potential, i.e. a continuous voltage potential difference value, each of the local electric field condensing area 1_i, i.e. each bored-through hole, behaves as a dipole which in fact superimposes a further electric field vector $\vec{E}$ with this further electric field being substantially directed along a symmetry axis of each bored-

through hole. It should be borne in mind that the electric field lines are thus distorted as shown at FIG. 3*a* or 3*b* at the level of each of the local electric field condensing areas 1_i.

For the sake of clarity and better comprehension, FIGS. 3*a* and 3*b* are shown in the absence of electric charges within the drift region and the detection region that in such a case fully corresponds to the absence of ionizing radiations. For instance, any virtual solid surface thereafter designated as FT which is delimited by the outermost electric field lines reaching one given local electric field condensing area, as shown at FIG. 3*a* for example, delineates an electric field tube FT in which the electric field flux presents a preservative character. As a consequence, it is clear to any person of ordinary skill in the corresponding art that the enhancement of the electric field at the level of each local electric field condensing area 1_i is thus given accordingly with any surface being passed through by the condensed electric field vector $\vec{E}'$ being in direct relation to the enhancement of the resulting electric field which is thus equal to the sum of original electric field vector $\vec{E}$ and superimposed electric field vector $\vec{E}'$.

Owing to the symmetrical character of the sandwich structure with respect to the symmetry plane referred to as plane Q at FIG. 3*a*, any virtual solid surface formed by the outermost electric field lines reaching a corresponding local electric field condensing area 1_i is substantially transferred as a symmetrical virtual solid surface formed by the electric field line leaving the same local electric field condensing area in the detection region, as shown at FIG. 3*a* with respect to the same electric field tube FT. As a consequence, provided given relations between voltage difference potential which is applied to the first **11** and the second **12** metal-cladding sandwiching the insulator foil **10** which will be explained later in the specification are fulfilled, it is thus clear that the distorted solid surface of electric field lines of the drift region is fully restored within the detection region as shown at FIG. 3*a*. It is furthermore emphasized that while the electric field $\vec{E}$ within the drift region and the electric field $\vec{E}''$ within the detection region are substantially parallel, they may well have amplitude of different value. As an example, the detection region electric field amplitude $|\vec{E}''|$ may be set up at a larger value than the drift region electric field amplitude $|\vec{E}|$ so as to increase the transfer velocity to the collecting electrode to get thus faster signals. The same situation occurs at FIG. 3*b* with the general form of the electric field lines being modified only by the spherical shape of the sandwich structure and more particularly its circular shape as represented at FIG. 3*b*.

A preferred embodiment of the gas electron mutiplier embodying a radiation detector in accordance with the present invention is now disclosed with reference to FIGS. 4*a*, 4*b* and more generally FIGS. 4*c* to 4*f*. As shown for example at FIG. 4*a*, the gas electron multiplier **1** may consist of a thin insulator foil referred to as **10** which is metal clad on each of its faces, the metal cladding being thus referred to as **11** and **12** with reference to FIGS. 2*a* and 2*b*, the sandwich structure thus formed being further traversed by a regular matrix of tiny holes referred to as 1_i. Typical values are 25 to 500 μm of thickness for the foil with the centre of the tiny holes being separated at a distance comprised between 50 and 300 μm. The tiny holes may well have a diameter which is comprised between 20 and 100 μm. The matrix of tiny holes 1_i is generally formed in the central area of an insulator foil of regular shape as shown at FIG. 4*a*. The insulator foil **10** is thus provided with electrodes on each of its faces which are referred to as **120** and **110**, these electrodes being thus adapted so as to apply a potential difference between the two metal sides of the mesh embodying the matrix of tiny holes. The composite mesh can thus be manufactured with conventional technologies which will be described later in the description, is simple to install rugged and resistant to accidental discharges.

The mesh as shown at FIG. 4*a* can be realized by conventional printed circuit technology. As an example, two identical films or masks are imprinted with the desired pattern of holes and overlaid on each side of the metal clad insulator foil **10** which is previously coated with a light sensitive resin. The insulator foil **10** may consist of a polymer such as KAPTON or the like, KAPTON being a registered trade-mark to DUPONT DE NEMOURS. Exposure to ultraviolet light and development of the resin exposes thus the metal to acid etching only in the regions to be removed, i.e. the tiny holes. The foils are then immersed into an adequate solvent for the polymer used and holes dig within the foils from the two sides by chemical etching. The whole processing uses common and well-known industrial procedures as though a precise control of the etching parameter are essential to obtain a reproducible mesh. The above-mentioned method is proper to allow the manufacturing of mesh from an insulator foil of thickness comprised between 20 to 100 μm for example. For insulator foils of greater thickness, i.e. of a thickness comprised between about 100 to 500 μm, alternative standard methods of manufacturing like plasma etching or laser drilling can also be used and provide similar results. One method of particular interest appears to be laser drilling since the process of drilling holes can be computed and controlled accordingly so as to obtain matrices of tiny holes of adapted shape with respect to corresponding application.

A detail of the mesh thus obtained is represented at FIG. 4*b*. Although the tiny holes shown at FIG. 4*b* are circular in shape, they may well be of different shape as it will be thus disclosed with reference to FIGS. 4*c*, 4*d* and 4*e*.

These figures consist of a front view of the mesh together with a cross-section view of this front view along a plane containing the center of symmetry of two successive tiny holes forming the matrix of tiny holes in the corresponding front view. With reference to FIGS. 4*b*, 4*c*, 4*d* and 4*e*, each tiny hole is deemed to be included within an opening aperture diameter which is comprised between 20 and 100 μm. While the tiny holes as shown at FIG. 4*b* are circular in shape with the outermost dimension of the holes fully corresponding to its aperture diameter, to the contrary, the tiny holes which are shown at FIGS. 4*c* and 4*d* fully correspond to square holes with rounded angles with the rounded angles corresponding to the opening aperture diameter of the hole.

The rounded angles allow to reduce the erratic electric discharges phenomenon.

At FIG. 4*e*, the tiny holes are represented so as to fully correspond to the tiny holes which are shown at FIG. 4*b*. In FIGS. 4*c*, 4*d* and 4*e*, parameters P, D, d, T and S designate:

- P the distance separating two successive tiny holes centers;
- D the outermost dimension of any square tiny hole;
- d the innermost dimension of any square tiny hole;
- T the thickness of the insulator foil **10**,
- S the thickness of the first **11** and second **12** metal cladding embodying the sandwich structure.

Corresponding values of the above-mentioned parameters P, D, d, T and S are thus given for FIGS. 4*c* and 4*d* with these dimensions being expressed in micrometers.

As shown as an example at FIGS. 4*c* and 4*d*, each bored-through hole 1_i consists of a bored-through hole which is formed by a first and a second frusto-conical bored hole. The first frusto-conical bored hole extends from the first metal-cladding **11** to an intermediate surface of the regular sandwich structure which is referred to as plane Q at FIGS. 3*a*, 3*b* and 4*c*, 4*e*. The second frusto-conical bored hole extends from the second metal-cladding **12** to the same intermediate surface referred to as plane Q, both frusto-conical bored-holes having a first circular opening of a diameter of a given value as previously mentioned in the description at the level of the corresponding metal-cladding **11** or **12**. Both of the frusto-conical bored holes join together at the level of the intermediate surface Q of the regular sandwich structure forming thus the corresponding bored-through hole 1_i as shown at FIGS. 4*c* and 4*e*. With the same pitch P of given value as previously mentioned in the description, the bored-through holes 1_i which are identical in shape and regularly distributed over all the metal clad faces of the insulator foil **10** form thus the matrix of tiny holes embodying the matrix of local electric field condensing areas in operation.

At FIG. 4*d*, a further particular embodiment of the matrix of tiny holes of the invention is shown in which each of the bored-through holes 1_i has a cross-section along a longitudinal plane of symmetry of this bored-through hole which is conical in shape.

Corresponding parameters are given now with respect to FIGS. 4*c* to 4*e* in which:

- P, T and S fully designate the same parameters as per FIGS. 4*c* and 4*e*, and
- D_1 designates the outermost dimension of one tiny hole formed at the level of first cladding **11**, for example;
- D_2 designates the outermost dimension for a square tiny hole which is formed at the level of the second cladding **12**;
- d_1 designates the outermost dimension for the bored-through hole within the insulator foil **10** at the level of first cladding **11**;
- d_2 designates the outermost dimension for the square bored-through hole through the insulator foil and at the level of second metal cladding **12**.

These dimensions are given in micro-meters. These parameters values are given thereafter as sizes example only with reference to tables I, II and III which are related to FIG. 4*c*, FIG. 4*d* and FIGS. 4*e*, 4*f* respectively.

TABLE I

P	D	d	T	s
140	110	60	50	15
200	130	70	50	18

TABLE II

P	D_1	D_2	d_1	d_2	T	s
200	160	120	75	60	50	5

TABLE III

P	D	d	T	d
200	130	100	50	18

Each of the bored-through holes 1_i as shown at FIG. 4*d* comprises thus a first and a second circular opening or substantially circular opening for given values which are different from each other and thus form a first and a second opening aperture diameter of different value at the level of the first **11** and the second cladding **12**.

FIG. 4*f* refers to another particular embodiment in which each of the bored-through holes is fully circular in shape, all the way through. The dimensions given at FIG. 4*f* may thus well correspond to those given at table III, with d being thus equal to D. Such a matrix as shown at FIG. 4*f* can be obtained by laser drilling.

A more detailed mode of operation of the gas electron multiplier **1** embodying the radiation detector of the invention is now disclosed with reference to FIGS. 5*a*, 5*b* and 5*c*.

In operation, when a potential difference is applied between the first and the second metal cladding **11** and **12** of the mesh, very high localized electric fields as vector $\vec{E}'$ previously mentioned in the description are created within the open channel in the tiny holes, as shown at FIGS. 3*a*, 3*b* and 5*a*, 5*b*, 5*c*.

The electric field enhancement as shown at FIGS. 3*a* or 5*a*, 5*b* is large enough to induce an avalanche multiplication from any primary electron entering one of the field tube FT of the drift region as shown at FIGS. 3*a*, 3*b* or 5*a*.

FIG. 5*b* represents the distribution of the electric field lines and the potential lines at the level of one electric field condensing area of the gas electron multiplier **1** embodying a radiation detector in accordance with the object of the invention, with the electric field lines being represented in solid lines and the potential lines in phantom lines. It is particularly emphasized that provided a given potential difference VGEM is applied to the first **11** and second **12** metal-cladding of the gas electron multiplier **1** embodying a radiation detector in accordance with the present invention, no electric field lines do reach either the first and second metal-cladding **11** and **12** or the insulator foil **10** as it is clearly shown at FIG. 5*b*.

It is also emphasized with reference to FIG. 5*c* that the electric field distribution along an axis of symmetry designated as X'X at FIG. 5*b* or 3*a*, 3*b* is substantially symmetrical with respect to the intermediate surface Q which is the plane of symmetry with respect to FIG. 5*b* as shown at FIG. 5*c*. It should be borne in mind that since no field line from the drift region except for the mathematical boundary between cells or field tube FT terminates on the upper electrode, any local electric field condensing area 1_i provides thus a full transmission of any drift electron as an electron avalanche, the gas electron multiplier **1** embodying the radiation detection of the invention providing thus a full electrical charges transmission and, as a consequence, an electrical transparency that substantially equals 1. This electrical transparency should be distinguished over the optical transparency of the mesh embodying the gas electron multiplier **1** since this electrical transparency substantially equal to 1 is obtained for an optical transparency of the mesh which is defined as the ratio between the total surface of all the tiny holes embodying the local electric field condensing areas over the total surface of the metal clad insulator foil and thus is comprised between 10% and 50%. It is further

emphasized that the high density of channels, i.e. of tiny holes, reduces thus the image distortions to values which are comparable to the intrinsic spread due to diffusion.

A particular embodiment of the radiation detector of the invention is now disclosed with reference to FIG. 6*a*.

The gain or the amplifying factor of the radiation is in a direct relationship to the amplifying factor yield by the gas electron multiplier as disclosed in the description. This amplifying factor is in a direct relationship to the electric field enhancement and more particularly to the electric field amplitude value along the symmetrical axis of symmetry X'X of each tiny hole embodying one electric field condensing area together with the path length of the electron avalanche within one of the local electric field condensing area, and as a consequence, the thickness of the metal clad insulator foil **10**. Insofar as the thickness is open to reach 100 μm with the tiny holes being drilled thanks to a laser processing as previously mentioned in the description, the amplifying factor which is defined as a ratio of the number of electrons of the electron avalanche entering the detection region to one primary electron yields those values to above 1000. With such a gain, or amplifying factor, the collecting electrode CE is adapted to operate at unity gain in ionization mode for example. In such a case, this electrode may consist of a plurality of elementary anodes as shown for example at FIGS. 1*a* to 1*c*, each elementary anode consisting for example of one strip or one pad of conductive material which allows an electronic detection of each electron avalanche. Each elementary anode as shown for example at FIGS. 2*a* and 2*b* is put at a reference potential such as a ground potential and is connected thanks to a capacitor CA to an amplifier A adapted to deliver a detection signal to a detection device which is not shown in the above-mentioned figures. The detection device is not disclosed for it is well-known per se to any person of ordinary skill in the corresponding art.

Thanks to its above mentioned electrical transparency that substantially equals one, the radiation detector of the invention may well be adapted to perform either monodimensional or bidimensional position detection. For such a purpose, as shown as a non-limitative example at FIG. 2*a*, the collecting electrode CE may be provided with elementary anodes ST_i which are laid onto the face of an insulator foil or printed circuit board facing the gas electron multiplier **1**, in case of monodimensional detection, with these elementary anodes each consisting of one electric conductive strip, these strips being thus parallel and extending along a first direction.

In case of bidimensional detection however further elementary anodes ST_j may be provided on the other side of the insulator foil, and separated from the first ones, so as to form parallel electric conductive strips extending along a second direction transverse to the first one. The conductive strips ST_i facing the gas electron multiplier **1** are preferably regularly spaced apart from each other so as to cover 50% only of the total surface of the collecting electrode CE, so as to allow any electron avalanche generated in front of any elementary anode ST_i facing the gas electron multiplier **1** to also induce a corresponding detection signal onto corresponding elementary anodes ST_i which are partially masked by the latters. The gain of detection amplifiers A embodying each detection circuit with capacitor CA and resistor RA may well be set up to different adapted values for each set of elementary electrodes, so as to introduce a good balance of the induced detection signal onto each set of elementary electrodes.

In order to improve the gain yield from the gas electron multiplier embodying a radiation detector in accordance with the invention as shown at FIG. 6*a*, a plurality of successive matrices of electric field condensing areas can be used, these matrices being in a cascade relationship over the primary electron stream, two matrices referred to as GEM_1 and GEM_2 being shown only for the sake of better comprehension at FIG. 6*a*. These successive matrices are put parallel to one another, i.e. in the absence of intersection, to define homothetic matrices over a common centre C forming the radiation detector as shown at FIG. 6*a*. As shown at this figure, two successive matrices are spaced apart from each other at a given separating distance value in a direction which is parallel to the corresponding electric field. As a consequence, the drift electrode DE, the first matrix or gas electron multiplier GEM_1, the second matrix or second gas electron multiplier GEM_2 and successive matrices together with the collecting electrode CE define therebetween successive electric fields which are referred to as vector $\vec{E}_{1D}$, vector $\vec{E}_{21}$, vector $\vec{E}$**02**and the like, each sucessive electric field allowing any primary electron or electron of one electron avalanche to drift as a primary electron along the separating distance thanks to its corresponding electric field.

The gas electron multiplier formed by successive matrices as shown at FIGS. 6*a* and 6*b* cooperates thus as an amplifier, the gain of which is the product of the gain yield for each successive matrix. FIG. 6*b* actually represents a planar embodiment of the radiation detector shown at FIG. 6*a*. It is further recalled that for planar embodiments as shown at FIG. 6*b*, the common center C actually lies at an infinite distance.

The radiation detector of the invention as it has been disclosed up to now with reference to FIGS. 1*a* to 6*b* fully operates as an amplifier, the collecting electrode CE of which operates at unity gain and can thus be made of a simple and very cheap stripped printed circuit for which the total gain or amplifying factor is obtained from the gas electron multiplier only, either single or multiple gas electron multiplier as shown at FIGS. 6*a* and 6*b*.

Another way to embodying the radiation detector of the invention is now disclosed in which the gas electron multiplier **1** is inserted into a host detector which has its proper gain with reference to FIGS. 7*a* and 7*b*. The host detector, in a general way, may consist as a non-limitative example, as a well-known micro-strip gas chamber, thereafter designated as MSGC, or a multiwire proportional chamber. As shown at FIG. 7*a* in case of a MSGC, the collecting electrode CE consists now of successive anode electrodes designated as AN and cathode electrodes, referred to as CO, which are interleaved and distributed over a dielectric support so as to form the collecting electrode CE. Each of the anode electrodes AN is connected to the reference potential referred to as the ground potential through resistor RA and to an amplifier A so as to allow detection while each of the cathode electrodes CO is connected to a bias potential generator VC, the MSGC chamber having thus its own gain depending on the gain which is yield through amplification between each of the cathode electrodes and anode electrodes. As further shown at FIG. 7*a*, one gas electron multiplier **1** is further inserted between the drift electrode DE and the collecting electrode CE so as to define a first drift region, $drift_1$, and a second drift region, $drift_2$, which are separated from each other by the gas electron multiplier **1**.

While proportional counters, multiwire chambers, and microstrip gas chambers, all exploit the basic amplification process of electron avalanche multiplication but differ only in their geometry and their performances, the maximum amplification factor that can be safely reached depends on many parameters and is limited by the probability of a

catastrophic hazardous discharge in case too large gains, i.e. too large voltages, are used.

As an example, the microstrip gas chamber which is made with its thin and fragile metal strips appears particularly exposed to discharge damages. The sophisticated electronic circuits connected to the strips such as amplifier A as shown at FIG. *7a*, can also be irreversibly damaged by these discharges.

Inserting a gas electron multiplier **1** as shown at FIG. *7a* within for example a microstrip gas chamber with the gas electron multiplier being inserted on the path of electrons drifting in the gas under the effect of a moderate electric field comes to effect to pull the primary electrons which are generated in the first drift region, $drift_1$, into the tiny holes forming the local electric field condensing areas and multiply them in an avalanche in the high local electric field and thus push them out from the other side, i.e. in the second drift region, $drift_2$, with the primary electrons being multiplied by a factor of many hundreds.

The gas electron multiplier **1** of the invention operates thus as a preamplifier of given gain for the primary electrons upstream the collecting electrode CE of the radiation detector.

Provided the bias potentials which are put to the drift electrode DE and the collecting electrode CE, particularly to the cathode electrode CO and the first and second metal-cladding **11** and **12** of the gas electron multiplier **1** as shown at FIG. *7a* are independent, such a configuration allows independent operation of the gas electron multiplier **1** and the microstrip gas chamber or multiwire proportional chamber as well as a controlled injection of ionization electrons into the preamplifying gas electron multiplier **1**.

Such mode of operation is called preamplification mode and can be used to largely increase the electric charges to be detected. Combined with a multiwire or a microstrip gas chamber, it makes much easier and safer to detect small amounts of electric charges. While the combination of a gas electron multiplier **1** adapted to a multiwire proportional chamber or a microstrip gas chamber of corresponding shape can be performed with these shapes corresponding to spherical or cylindrical ones, the preamplification mode of operation of the gas electron module **1** of the invention appears of highest interest in case of multiwire proportional chamber or microstrip gas chamber of planar structure, the gas electron multiplier **1** in such a case corresponding also to a planar structure as shown at FIG. *7a*.

As per FIGS. *6a* or *6b* to which the gas electron multiplier operates in amplification mode, combining several successive gas electron multipliers as shown at FIG. *7b* appears of outmost interest so far these gas electron multipliers are adapted to operate independently since it is thus possible to achieve increasing large gains in a succession of elements with each of the elements being individually set at moderate amplification factor and therefore intrinsically safer to operate. As shown at FIG. *7b*, two successive gas electron multipliers, referred to as GEM_1 and GEM_2, are shown to embody a resulting gas electron multiplier with each gas electron multiplier GEM_1, GEM_2 being set to yield a gain or amplifying factor to 100. The resulting amplifying factor is thus the product of each gain, then, as a consequence, has a value that equals 10 000.

Irrespective to its mode of operation, in order to operate the radiation detector of the invention which is shown at FIGS. *6a*, *6b* or *7a*, *7b*, the voltage potentials can be set up at the following values:

conducting strips of the collecting electrode CE of FIGS. *6a* or *6b* at the reference potential referred to as the ground potential;

anode AN of the collecting electrode CE of FIGS. *7a* or *7b* at the reference potential.

All the other voltage potentials set up with respect to the reference or ground potential. The following potential values are given as a non-limitative example for a given A-CO_2 (argon-carbondioxide) gas mixture, as shown at FIG. *8a*, given gas electron multiplier geometry embodying an insulator foil **10** of thickness 50 μm and tiny holes of diameter 100 μm, this gas electron multiplier being operated with this gas mixture being at atmospheric pressure. Change of any parameter would imply correlative changes in the ranges of voltage potential values.

cathode potential VC to each cathode electrode CO at FIG. *7a* or *7b*, Vc=−500 V;

V_4 set up between −100 V and −1000 V;

V_3 set up between −600 V and −1500 V with V_{GEM}=−500 V;

V_2 set up between −1600 V and −2300 V;

V_1 set up between −2100 V and −2800 V with V_{GEM}=−500 V.

The distances separating the gas electron multiplier from the drift electrode, or the successive electrode CE were set up to 3 mm.

A multistage detector in accordance with the invention operating in either amplification or preamplification mode is thus functionally equivalent to a multidynonde photomultiplier except it operates in a gaseous environment while each matrix element of local electric field condensing areas has a much larger gain.

As compared to similar gas devices realized with stretched parallel metal meshes, the so-called parallel plate and multistep chambers, the gas electron multiplier which is the object of the invention is fully self-supporting since the multiplying gap and therefore the gain are kept substantially constant by the fixed thickness of the insulating foil regardless of the precise location of the gas electron multiplier within the detector or the host detector. Furthermore, heavy support frames are not necessary, this greatly simplifying construction and increasing reliability while reducing costs.

EXPERIMENTAL OBSERVATIONS

Extensive experimental measurements were realized with several types and models of gas electron multipliers, meshes as self-standing one's operating in amplification mode or in combination with host detectors and have been described in papers which are listed thereafter:

*Nuclear Instrum. Methods, Methods in Phys.Res.*A386 (1997)531; F. SAULI;

IEEE *Trans.Nucl.Sci.* NS-(1997); R. BOUCLIER, M. CAPEANS, W. DOMINIK, M. HOCH, J-C. LABBE, G. MILLION, L. ROPELEWSKI, F. SAULI and A. SHARMA;

CERN-PPE/97-32; R. BOUCLIER, W. DOMINIK, M. HOCH, J-C. LABBE, G. MILLION, L. ROPELEWSKI, F. SAULI, A. SHARMA and G. MANZIN;

Progress with the Gas Electron Multiplier, CERN-PPE/97-73; C. BUETTNER, M. CAPEANS, W. DOMINIK, M. HOCH, J-C. LABBE, G. MANZIN, G. MILLION, L. ROPELEWSKI, F. SAULI, A. SHARMA.

During those experimental measurements, preamplification factors above 100 have been observed in many gases and gas mixtures of noble gases such as helium, argon, xenon or the like with organic or inorganic quenchers like carbon dioxide, methane and dimethylether. FIG. *8a* gives

some examples of the gas electron multiplier amplification factor which is plotted in relation to the potential difference which is applied to the first and second metal-cladding **11** and **12** embodying one gas electron multiplier **1** in accordance with the invention. Experimental results as shown in FIG. **8***a* are given for a first mixture of:

Argon and dimethylether, thereafter designated as A_DME with 90% argon and 10% DME;

Argon and carbon-dioxide thereafter designated as A_CO_2 with a ratio of 90% argon and 10% CO_2;

Helium and methane, thereafter designated as $He_{\_CH4}$ with a ration of 70% helium and 30% methane;

Argon and dimethylether, thereafter designated as A_DME with a ratio to 50% argon and 50% DME.

Preceding ratios are given as volume ratios.

The voltage difference which was applied to the first **11** and second metal-cladding **12** was comprised between 200 and about 600 volts, thereafter designated as V_{GEM}.

Most measurements have been realized at atmospheric pressure convenient for the manufacture and operation of light and safe detectors but correct performance at pressure between few millibars and 10 bars revealed satisfactory.

A fundamental property of the gas electron multi plier embodying one radiation detector in accordance with the invention appears to be the wide range of electric fields strengths that can be applied above the mesh forming the matrix of local electric field condensing areas without affecting the gain actually yield. Such a property appears of highest importance because it makes the gas electron multiplier of the invention almost insensitive to large mechanical variations in the surrounding electrodes. As a consequence, such a property allows the choice of the drift field for optimal physical requirements as the value of the electrons drift velocity, diffusion and collection time.

A concern of high-rate applications is the behaviour of the gas electron multiplier embodying the radiation detector in accordance with the present invention under condition of large detected currents. While most of the electric charges, electrons and positive ions, smoothly drift in the open gas channel without affecting the operation, some stray charges may collect on the surface of the insulator with these stray charges distorting the field and therefore the gain thus obtained. It has been however demonstrated that a very small surface conductivity in the channel which is obtained very simply by the addition to the gas of a small amount not exceeding 1% of water vapor completely stabilizes the operation up to detected X-ray fluxes of 10^7 Hz cm^{-2} or more.

Other methods of increasing the surface conductivity to the desired value have been investigated such as ion implantation or vacuum evaporation of semi-conducting layers. It has thus been observed that using a polymeric foil embodying the insulator foil **10** with an intrinsic resistivity between 10^{12} and 10^{13} Ω×cm would properly solve the charging up problem in a natural way.

As a consequence, as it is shown at FIG. **8***d*, each tiny hole or bored-through hole $\mathbf{1}_i$ is provided with an internal lateral surface which is delimited by the insulator foil **10**. As clearly shown at FIG. **8***d*, this lateral surface comprises preferably one local zone with intrinsic resistivity between 10^{12} and 10^{13} Ω×cm. In a non-limitative way, as shown at FIG. **8***d*, this local zone is deemed to cover the extremal portion of the frusto-conical bored-through hole in which electric charges such as positive ions have been introduced through ion implantation for example.

With reference to FIG. **8***d*, it is clear to one of ordinary skill in the corresponding art that, thanks to the presence of the positive electric charges which are implanted at the extreme part of the frusto-conical profile of the insulator foil with these electric charges being distributed substantially with the same concentration all around the periphery of the tiny hole, i.e. in the vicinity of the medium plane or symmetry plane Q which was already mentioned with reference to FIG. **5***b*, the electric field lines are made very tight at the level of the intermediate plane or symmetry plane Q shown at FIG. **8***d* with the electric field being thus accordingly increased thanks to the preservative character of its flux within the modified solid surface or field tube FT through the presence of the implanted electric charges.

To detect the amount of the electrical charges which are released into a gas by soft X-rays or fast particles, about 100 electrons, amplification factors of 10 000 or so are necessary, given the limitations of modern highly integrated electronics. This can be achieved safely by combining one gas electron multiplier mesh with an amplifying factor of 100 together with a multiwire or microstrip gas chamber safely operated also at a gain of 100. The discrete nature of the electrodes in the host detector which are wires or strips allows then to achieve the electron avalanche localization.

It is also clear to one of ordinary skill in the corresponding art that this can also be achieved thanks to a radiation detector operating as an amplifier in which the collecting electrode CE is put at unity gain so far the gas electron multiplier **1** is enough thick to yield corresponding value of amplifying factor equal to 10 000 with the thickness of the sandwich structure being thus open to reach a thickness substantially equal to 500 μm, or by a multistage gas electron multiplier as shown at FIG. **6***a* or **6***b* for example.

Another fundamental property of the gas electron multiplier embodying the radiation detector of the invention is its high-rate capability while the gain or the relative pulse height of the radiation detector is substantially maintained at a constant value over its full rate range.

While the gain of the gas electron multiplier in accordance with the present invention has been defined as the ratio of the electrons number in the electron avalanche leaving the output face to the number of electrons of the primary electrons or the electrons entering the input face at the level of each local condensing area of the matrix embodying the gas electron multiplier, one mode of operation to evaluate such a gain may consist as an example to measure the preamplification factor or the amplification factor which is defined as a ratio of the most probable pulse height between transferred and direct spectra for the 5.9 keV line radiated by an external ^{55}Fe source.

As shown at FIG. **8***b*, the relative pulse height PH is plotted with respect to the rate expressed in Hz/mm^2 in three modes of operation of a gas electron multiplier inserted within a host detector which consists of a microstrip gas chamber in the following situations:

micro-strip gas chamber only,

gas electron multiplier only, and

multi-strip gas chamber and gas electron multiplier joined together.

The results which are shown at FIG. **8***b* clearly confirm the high-rate capability for the charge gain remains essentially constant within few percent up to the maximum rate that could be achieved, around 10^5 Hz/mm^2, regardless of the mode of operation thus demonstrating the absence of short-term ion induced charging up or charge space effects in the local electric field condensing areas.

One should also note that the fraction of ions receding into and through the gas electron multiplier local electric field condensing areas depends on the applied voltages. In the

mode of operation of unity gain of the micro-strip gas chamber with the gas electron multiplier being operative only, there are no positive ions produced in the lower gas volume and presumably no substrate charging up and ageing problems.

Another fundamental property of the radiation detector in accordance with the present invention which is embodied through a gas electron multiplier fully concerns the absence of time-dependent gain shifts.

While the presence of an insulator material close to the multiplication channels or the tiny holes is open to introduce the possibility of dynamic gain shifts due to the deposition of electric charges and the consequent modification of electric fields, this drawback can thus be fully overcome as already mentioned previously in the description, either by using a wet gas mixture in which a given proportion of water vapor is introduced or by giving particular values of electric conductivity to given zones of the internal part of each tiny hole forming a corresponding local electric field condensing area, as previously mentioned in the description.

With respect to this last solution consisting for example in implanting positive ions as it is shown at FIG. **8***d*, it is also emphasized that it comes to effect to repel the positive charges which are possibly generated by the electron avalanche towards the symmetry axis X'X as shown at FIG. **8***d* thereby allowing to reduce the charging up phenomenon of the insulator foil internal lateral surface while the electrons of the electron avalanche are quite unaffected by the presence of the implanted ions. The residual electric charges which are charged up by the internal lateral surface of the insulator foil has thus its contribution to the total electric field distortion drastically reduced, the charging up phenomenon being thus overcome.

FIG. **8***c* shows the variation of the pulse amplifying factor of one gas electron multiplier **1** in accordance of the object of the present invention, with this amplifying factor being plotted over the time during which the gas electron multiplier **1** is actually on, the time being expressed in minutes.

Corresponding curve I is given for a gas electron multiplier operated with a potential difference applied to the first **11** and second **12** metal-cladding of the sandwich structure which was put to 420 volts with the radiation detector being filled with a gas mixture of argon and carbon dioxide to a ratio 72%/28%.

The charging up phenomenon comes up to effect to increase the pulse amplifying factor for an initial value that equals 40 to a value greater than or substantially equal to 52 after 20 minutes the radiation detector is on.

Corresponding curve II is given for the same radiation detector as it was used to get curve 1 except that the gas mixture is further provided with water vapor to 0.35% in addition.

Curve II clearly shows the full constant character of the pulse amplifying factor which substantially equals 40 all over the time the radiation detector of the invention is on, that is from the very beginning to the end of the experiment 50 minutes later.

It should be thus understood that after the addition of water vapor, the inter-electrode resistivity of the gas electron multiplier mesh decreases gradually by a factor of 10, from 100 to 10 GΩ, and then remains constant. Taking into account the total area of the channels and particularly of the tiny holes embodying the latters, this clearly indicates that a surface resistivity around 10^{16} Ω/square is sufficient to eliminate the charging up phenomenon as the highest rates. The original value of resistivity as well as the final one after introduction of water depend on the total area and the number of tiny holes. Preceding values refer to a 10×10 cm^2 gas electron multiplier **1** provided with about 5×10^5 tiny holes.

Particular embodiments well adapted to specific applications are now described with reference to FIGS. **9***a*, **9***b* and **9***c*.

Each of the above-mentioned embodiments is well adapted to operate either on amplification or preamplification mode as previously disclosed in the description. It is furthermore emphasized that the amplification mode may well be preferred for applications in which ionizing radiations of very high energy level are to be investigated.

Accordingly, FIG. **9***a* shows the radiation detector of the invention in which the sandwich structure forming a gas electron multiplier **1** is provided which is spherical in shape. This radiation detector may well correspond to that which is shown at FIG. **1***c* with the external form of the detector being circular in shape as shown at the front view of FIG. **9***a*. This radiation detector is adapted to crystallography trials in which X rays are directed to a crystal, the radiation detector of the invention being thus adapted to allow a full detection of the diffraction pattern generated by the impingement of the X-rays onto the crystal. As clearly shown at FIG. **9***a*, the bored-through holes forming the electric field condensing areas are regularly distributed over a part only of the metal-clad faces of the insulator foil so as to form at least one blind detection zone which is referred to as BZ for the radiation detector. The blind detection zone is thus substantially spherical in shape and located at the center part of the sandwich structure with the bored-through holes being distributed all around this blind detection zone so as to allow detection of the diffraction pattern out of this blind detection zone only. Particularly in case the radiation detector of the invention as shown at FIG. **9***a* is used in amplification mode, that is in the absence of micro-strip or multiwire chamber as final amplifier, it allows to adapt the collecting electrode CE shape to the needs with this electrode for example consisting of strips, pads or rings, the rings being particularly adapted in case of crystal diffraction measurements. At FIG. **9***a*, the rings forming the collecting electrode CE are shown in phantom line for better comprehension and clarity of the drawings.

FIGS. **9***b* and **9***c* are concerned with radiation detectors in accordance with the present invention which are more particularly adapted and suited for colliding beams accelerators or very high energy particles colliding ring accelerators like that which is in operation at the CERN (Centre Européen de Recherche Nucléaire) in Geneva, Switzerland. At FIGS. **9***b* and **9***c*, the colliding ring accelerator, owing to its very high curvature radius, is represented as a straight portion. As shown at FIGS. **9***b* and **9***c*, the gas electron multiplier embodying the radiation detector in accordance with the invention consists of a solid surface made of adjacent elementary solid surfaces, each elementary solid surface forming one elementary gas electron multiplier which comprises at least one matrix of electric field condensing area so as to form elementary detectors which are referred to as RD_1 to RD_9. The elementary detectors are joined to one another so as to form a three-dimensional radiation detector which surrounds the colliding ring accelerator as shown at FIGS. **9***b* and **9***c*.

The three-dimensional detector shown at FIG. **9***b* is spherical in shape and formed from elementary radiation detectors which are each spherical in shape and fully correspond to the radiation detector in accordance with the present invention which is shown at FIG. **1***c* with elementary detectors RD_1, RD_2, RD_3 and RD_4 being designed so as to

form a skullcap while the other elementary detectors are design as a part of a corresponding volume spherical in shape. Elementary detectors RD_2 and RD_3 may well be provided with a central blind detection zone, as already shown at FIG. 9*a*, this blind detection zone being further drilled so as to allow the colliding ring accelerator to pass through. Each elementary radiation detector may be manufactured as the radiation detector shown at FIG. 1*c* by thermo-forming all its constituting parts such as the input window and drift electrode, the sandwich structure and the collecting electrode CE together with the intermediate frames which are necessary to build up any radiation detector or elementary radiation detector in accordance of the present invention. As shown at FIG. 1*a* or 1*c*, in order to embody one elementary radiation detector as shown at FIG. 9*b* or 9*c*, the gas inlet and gas outlet GI and GO may be removed and replaced by bored-through holes with the bored-through holes forming the gas inlet and gas outlet of two neighbouring adjacent elementary radiation detectors, such as RD_2 and RD_5 at FIG. 9*b*, these bored-through holes being put to face each other and to be sealed thanks to O rings. The electrodes terminals which are adapted to apply the difference potential to the input and output face formed by the first and second metal-cladding **11** and **12** as shown at FIGS. 1*a* and 1*c*, are reduced and adapted to further allow the interconnecting of the first and second metal-cladding respectively of two successive adjacent elementary radiation detectors, the same difference potential voltage being thus applied to each gas electron multiplier embodying each elementary radiation detector which as a consequence yield the same gain.

As further shown at FIG. 9*a*, one general gas inlet GI and gas outlet GO only are provided which are preferably located close the blind zone in the vicinity of the colliding ring accelerator. The same for the electrodes **110** and **120**, one of these electrodes only being thus provided to allow a same difference voltage potential VGEM to be applied to each elementary first **11** and second **12** metal-cladding.

FIG. 9*c* is directed to a three-dimensional radiation detector which is substantially cylindrical in shape at the extremities of which two elementary half-spherical radiation detectors are abutted. The elementary half-spherical radiations detectors may well consist of one or several elementary radiation detectors thereafter designated as RD_1, RD_2, RD_8, RD_9 with elementary radiation detectors RD_1 and RD_9 playing the same role as the elementary detectors as RD_2 and RD_3 at FIG. 9*b*. The length of the cylindrical part as shown at FIG. 9*c* may extend along the colliding ring accelerator for several meters with this cylindrical part consisting of several adjacent elementary radiation detectors thereafter designated as RD_3 to RD_7. In order to allow three-dimensional radiation detectors of great dimensions to be operated, the inner part of these detectors as shown at FIGS. 9*b* and 9*c* may well be filled outside the inlet window of each elementary radiation detector with a foam which is substantially transparent to the X or gamma rays of very high energy.

A radiation detector of very high efficiency, in accordance with the present invention, has thus been disclosed in which a gas electron multiplier may be used in the field of elementary particle experiments.

Generally speaking, embodying a radiation detector in accordance with the invention operating in the preamplification mode with the gas electron multiplier mounted within a micro-strip gas chamber for example, allows to operate such a sophisticated but fragile device in much safer conditions.

Several new experiments embodying a gas electron multiplier in accordance with the object of the invention were actually conducted.

One first new approved experiment, thereafter designated as HERA-B at DESY in Hamburg, Germany (DESY, for Deutsche Elektron Synchrotron) qualified and adopted the gas electron multiplier of the invention, in order to improve the reliability of the high rate host tracking detector.

One second new approved experiment, thereafter designated as COMPASS at CERN, came to adopt the gas electron multiplier technology in accordance with the invention for similar reasons.

Another proposed new experiment designated as FELIX and conducted at the CERN (Centre Européen de Recherche Nucléaire) in Geneva is carried out so as to improve radiation detectors operating in the amplification mode in the cylindical geometry.

Another detector, thereafter designated as HELLAZ, is proposed for large cosmic rays experiment in the Italian Laboratory under the GRAN SASSO with the aim of achieving large enough gains to detect single electrons.

A further particular use of the gas electron multiplier of the invention may also consist to prevent transmission of electrons and/or ions through the control of external voltages. As shown for example at FIG. 2*a* or 2*b*, the biasing source **2** may well consist of two detening voltage generators of opposite polarity that can be switched through a common switch K. Operating the switch K allows the difference voltage potential VGEM to be reversed so as to allow to prevent transmission of electrons and/or ions, the sandwich structure operating thus as an active gate, the enhanced electric field being thus strong enough to repel given electric charges ions or electrons.

A further embodiment of the radiation detector in accordance with the object of the present invention is now disclosed with reference to FIG. **10**.

This embodiment is more particularly directed to a radiation detector for photons which are emitted by an external source.

The operating principle of the gas electron multiplier **1** which is the object of the present invention operating as a photon detector relies on the following specific properties of its structure:

- a controlled electrical transparency, from 0 to 1, actually depending on the voltage potentials which are applied on the various electrodes of a composite structure operating either as an amplifier or a preamplifier and including thus a gas electron multiplier as previously disclosed in the description;
- a geometry controlled optical transparency from about 10% to 50% which is obtained by appropriate patterning during manufacturing;
- a demonstrated operation with gain in pure and inert gases which actually proved harmless to photocathode materials, and the existence of photocathode materials operating in many particular wavelengths either visible or invisible ones that have large quantum efficiency and long survivability in a gaseous environment.

The schematics of a reverse photocathode, gas electron multiplier, photon detector in accordance with the object of the present invention is shown at FIG. **10** together with its corresponding features and electric field lines.

As previously disclosed in the description with reference to FIG. 3*a* for example, the radiation detector for photons which is the object of the present invention consists of a vessel, which is not shown at FIG. **10** for the sake of better comprehension, with this vessel being filled with a gas

adapted to generate an electron avalanche from a primary electron through an electric field.

An inlet window IW is further provided which is associated with a transparent electrode denoted as C, this inlet window and transparent electrode being adapted to transmit the photons within the gas contained by the vessel. The inlet window IW and transparent electrode C are made of a material which is substantially transparent to the photons wavelength. Well-known technology may be used so as to put the inlet window IW and the transparent electrode C together, the transparent electrode for this reason being represented with phantom line only at FIG. **10**.

As further shown at the above-mentioned figure, a photocathode layer, denoted as PhC, faces the transparent electrode C with this photocathode layer being adapted to generate one photo-electron as a primary electron under impingement of each one of the photons onto this photocathode layer.

A gas electron multiplier **1** is further provided so as to include at least, as previously mentioned in the description, one matrix of electric field condensing areas which is formed from the foil metal clad insulator **10** provided with metal cladding **11** and **12** onto its faces, with metal cladding **11** facing the transparent electrode C. As clearly shown at FIG. **10**, the photocathode layer PhC, the metal claddings **11** and **12** together with the insulator foil **10** form thus a regular sandwich structure as previously mentioned in the description. Furthermore, a plurality of bored-through holes denoted 1_i traverse thus the regular sandwich structure with each of the bored-through holes being adapted to allow a free flowing therethrough for the gas and any electrically charged particle generated within the latter. As a matter of fact, in order to embody the electron gas multiplier **1** as shown at FIG. **10**, one may well have first a metal clad insulator provided with metal claddings **11** and **12** onto one of the faces of which a layer of photosensitive material is deposited so as to build up the photocathode layer PhC. The bored-through holes may thus be drilled according to anyone of the technologies which are actually disclosed in the description.

As shown at FIG. **10**, inlet window IW and transparent electrode C are spaced apart to form a convey region which operates in a similar way as the drift region of FIG. **3***a*, as it will be disclosed in more details later in the description.

On the bottom side of the vessel, the detector of the invention further includes a detection unit adapted to perform a position detection of any electron avalanche generated within the detection region which is formed between the gas electron multiplier **1** and the detection unit as shown at FIG. **10**. For the sake of better comprehension, the detection unit is represented as a collecting electrode CE as previously mentioned with reference to FIGS. **2***a* or **3***a*. It is further emphasized, although not represented for the sake of better comprehension at FIG. **10**, that the detection unit may well include another gas electron multiplier so as to form a multistage gas electron multiplier as previously mentioned in the description or a microstrip chamber or even a multiwire chamber for example.

To the contrary, as shown at FIG. **10**, the top electrode of the collecting electrode CE is provided with elementary anodes, each of which is denoted ST_i, with these elementary anodes consisting for example as parallel electric conductive strips which are laid onto an insulator foil denoted CEF. Electronic circuits consisting of resistor RA, capacitor CA and amplificator A, are further provided as previously mentioned in the description.

As further shown at FIG. **10**, a biasing circuit referred to as B_1, is provided and adapted so as to maintain the transparent electrode C and the first metal cladding **11** substantially to the same voltage potential value with respect to the reference potential value so as to allow extraction of any photo-electron which is generated by the photocathode layer PhC under impingement onto the latter of each one of the emitted photons. Biasing circuit B_1 is represented thus as a short-circuit conductor.

A further biasing circuit, referred to as B_2, is provided so as to develop a bias voltage potential referred to as VGEM which is applied between the metal claddings **11** and **12** so as to form at the level of each of the bored-through holes one of the electric field condensing areas 1_i as previously mentioned in the description. Applying such a voltage allows thus to generate a condensed electric field denoted as vector $\vec{E}'$ within each of the electric field condensing area.

Another biasing circuit, referred to as B_3, is further provided so as to develop a bias voltage potential which is actually applied between metal-cladding **12** and collecting electrode CE and more particularly elementary anodes referred to as ST_i at FIG. **10** so as to allow the detection of the electron avalanche as it will be explained thereafter.

At first, it is recalled that each elementary anode ST_i forming part of the collecting electrode CE is substantially set up as a reference potential thanks to resistor RA which is a resistor of very high value connecting each corresponding elementary anode to the reference potential.

The mode of operation of the radiation detector for photons as shown at FIG. **10** is now explained with reference to this figure.

Maintaining the transparent electrode C and the metal-cladding **11** which faces the transparent electrode substantially to the same voltage potential value thanks to biasing means B_1 comes to effect to put the electric field vector $\vec{E}$ shown at FIG. **3***a* to a value that substantially equals 0.

As a consequence, each condensed electric field vector $\vec{E}'$ generated within each electric field condensing area, which is thus an electric field of very high amplitude value, operates thus within the region delimited between the transparent electrode C and the metal-cladding **11** and photocathode layer PhC as to convey each of the photoelectron to one given electric field condensing area which is the closest of the impingement region of this photon within the fill tube FT which is actually generated between metal-cladding **11** and collecting electrode CE, as shown at FIG. **10**. Cancelling the electric field vector $\vec{E}$ with its amplitude being quite set up to zero value in the vicinity of transparent electrode C as shown at FIG. **10** comes thus to the effect of substituting a convey region to the drift region which is represented at FIG. **3***a*. As a consequence, the field tube FT is thus folded back to the metal-cladding **11** with any photo-electron being thus conveyed to within a corresponding electric field condensing area 1_i. The condensed electric field vector $\vec{E}'$ operates thus to generate from this photo-electron regarded as a primary electron one electron avalanche within corresponding bored-through hole with this electron avalanche being thus passed through this bored-through hole to the detection region, as shown at FIG. **10**. The electron avalanche is thus submitted to detection thanks to electric field vector $\vec{E}''$ and elementary anodes ST_i of the collecting electrode CE.

For distances separating on the one hand the transparent electrode C from the photocathode layer PhC and on the other hand metal-cladding **12** from elementary anodes ST_i defining thus the convey region and the detection region, which have quite the same values as those previously

mentioned with reference to FIG. 3*a*, corresponding voltage potential values may well be set up to similar values. As a consequence, potential value VGEM may well be set up to 500 volts while potential value applied between metal-cladding **12** and elementary anodes ST_i may be set up to 1000 volts, with this values being thus given as an example.

As further shown at FIG. **10**, position detection of any avalanche which is passed through any electric field condensing area 1_i may preferably be performed as a bidimensional detection. In such a case, while the inner face of the collecting electrode CE is provided with a first set of elementary anodes ST_i, the outer face of same collecting electrode CE is thus provided with another set of elementary anodes referred to as ST_j consisting also of parallel electric conductive strips, with each of the sets of elementary anodes ST_i and ST_j extending along distinct transverse directions so as to allow bidimensional detection in corresponding directions.

In case a further electron gas multiplier is used so as to embody a multistage radiation detector for photons, the multiplied electrons by the high field in the hole in avalanche process drift to the second element of amplification for further amplification.

A fundamental property of the radiation detector for photons either as single stage or multistage version, which cannot be obtained with any other known gas detector, is that secondary photons produced during the electron avalanche process, both primary in the bored-through holes forming each electric field condensing area of the gas electron multiplier and secondary in the second stage element, cannot heat the photocathode layer PhC thereby preventing to induce secondary emission.

The high dipole field which is created within the bored-through holes allow thus to obtain a collection efficiency, i.e. electrical transparency close to unity with an optical transparency close to zero.

The large ratio of the total area to the holes area implies also that most of the surface of the metal-cladding **11** an thus be coated by photosensitive material with a geometrical quantum efficiency close to 1. The field configuration which is obtained with a large difference of potential between metal-cladding **12** and elementary anodes ST_i is such that only a small fraction of the positive ions which are produced at the final amplification stage can thus actually reach the photocathode layer PhC reducing thus the damage effects.

The radiation detector for photons in accordance with the object of the present invention permits thus to obtain simultaneously:

large quantum efficiency of over extended areas,

large gains without photons feed-back and very reduced ions feed-back.

The total combined gain of the two amplification elements in case of a multistage gas electron multiplier may thus be set up to a value sufficient enough for the detection and localization of single photo-electrons opening thus the way to numerous scientific, technical or industrial applications like CHERENKOV ring imaging, image intensifiers, fluorescence analysis in the visible and near ultraviolet range, or any applications requiring detection and localization of photons over extended areas.

The rigid and simple construction of gas electron multiplier detectors in accordance with the object of the present invention, either in preamplification or amplification mode, makes them interesting for applications in many fields where low and high rate detection and localization of radiation can be exploited for industrial or medical diagnosis.

Medical diagnosis covers corresponding medical fields as large as:

Radio and beta-chromatrography, electrophoresis in which anatomical preparations or blot paper diffusions contain molecules labelled with electron emitting isotopes, the two-dimensional activity distribution measured on slide samples which provides information on the tissue in take off labelled molecules or on the molecular weight of substances diffusing on a support under the effect of electric field;

Position-dependent fluorescent analysis in which the capability of simultaneous obtention of information on the energy and the emission point of soft X-rays over extended areas can be exploited for material analysis in Archeology and Art certification;

Protein crystallography which is realized in a spherical geometry for which gas electron multipliers detectors can map without parallax distortions both position an intensity of the diffraction pattern of crystallized molecules. High rates are achievable at the dedicated synchrotron radiation facilities;

Mammography in which a gas electron multiplier in accordance with the invention when coupled to a secondary electron emitted converter can effectively map the absorption profile of X-rays which are used for soft tissue radiography, with a sub-millimeter resolution;

High flux beam diagnosis which is used for therapy in which high flux charged particle beams can be fully certified in spatial and energy loss profiles before or during exposure. In such an application, the dynamic control of the beam characteristics is thus possible.

One further possibility of the radiation detector of the invention also concerns the possibility for the gas electron multiplier to be tailored to applications or specific needs and particularly its shape with special cut outs as for approaching vacuum beam tubes in accelerators or the like.

At end, while present technologies which are used to manufacturing the gas electron multiplier embodying the radiation detectors of the invention do consist in drilling holes on metal clad by chemical etching, plasma etching or laser drilling, future developments may consist in coating with conductors an insulating mesh with narrow holes like for example micropore filters.

What is claimed is:

1. A radiation detector in which primary electrons are released into a gas by ionizing radiations and are caused to drift to a collecting electrode by means of an electric field, said radiation detector including a gas electron multiplier comprising at least one matrix of electric field condensing areas, said electric field condensing areas being distributed within a solid surface which is substantially perpendicular to said to said electric field, each of said condensing areas producing a local electric field amplitude enhancement sufficient to generate in said gas an electron avalanche from one of said primary electrons so that said gas electron multiplier operates as an amplifier of a given gain for said primary electrons,

said matrix of electric field condensing areas comprising:

an insulator having first and second foil metal claddings on opposed faces thereof forming a sandwich structure;

a plurality of through holes traversing said sandwich structure; and

biasing means for developing a bias voltage potential which is applied to said first and second metal claddings so as to generate, at each of said through holes, one of said electric field condensing areas, and

said sandwich structure being disposed substantially perpendicular to said electric field, said first metal

cladding forming an input face for said drift electrons and said second metal cladding forming an output face for any electron avalanche generated at each through hole forming one of said electric field condensing areas.

2. The radiation detector of claim 1, wherein said local electric field amplitude enhancement generated by each of said condensing local areas is substantially symmetrical in relation to an axis of symmetry of said condensing local area, so that said local electric field amplitude enhancement is at a maximum at the center of symmetry of said condensing local area.

3. The radiation detector of claim 1, wherein said electric field condensing areas are substantially identical in shape and regularly distributed within said solid surface so as to form said matrix.

4. The radiation detector of claim 1, wherein said through holes are substantially identical and circular in shape in viewed in a direction substantially perpendicular to said sandwich structure.

5. The radiation detector of claim 1, wherein each of said through holes is formed by first and second frusto-conical bored holes said first frusto-conical bored hole substantially extending from said first metal-cladding to an intermediate surface of said sandwich structure and said second frusto-conical bored hole substantially extending from said second metal-cladding to said intermediate surface of said sandwich structure, said first and second frusto-conical bored holes each comprising a first circular opening of a diameter of a first given value at the level of said input and output faces respectively to and a second circular opening of a diameter of a second given value, smaller than the first ones, said second circular opening of said first and second frusto-conical bored holes joining together at the level of said intermediate surface of said sandwich structure so as to form said bored-through hole.

6. The radiation detector of claim 1, wherein said through holes are identical in shape and regularly distributed over all of the metal clad faces of said insulator foil.

7. The radiation detector of claim 1, wherein said through holes are identical in shape and regularly distributed over a part of the metal clad faces of said insulator foil so as to form at least one blind detection zone for said radiation detector.

8. The radiation detector of claim 1, wherein said solid surface is a planar surface.

9. The radiation detector of claim 1, wherein said solid surface is spherical in shape.

10. The radiation detector of claim 1, wherein said solid surface is cylindrical in shape.

11. The radiation detector of claim 1, wherein said solid surface comprises adjacent elementary solid surfaces, each of said elementary solid surfaces forming thus one elementary gas electron multiplier comprising at least one matrix of electric field condensing area.

12. The radiation detector of claim 1, in which said collecting electrode is adapted to operate at unity gain, in an ionization mode, said collecting electrode at least comprising a plurality of elementary anodes allowing an electronic detection of each electron avalanche.

13. The radiation detector of claim 1, comprising a plurality of successive matrices of electric field condensing areas, said successive matrices being disposed parallel to one another to define homothetic matrices over a common center forming said gas electron multiplier and two successive matrices of said successive matrices being spaced apart from each other by a given separating distance in a direction parallel to said electric field forming a first electric field so as to define therebetween successive electric fields and to allow any electron of one electron avalanche to drift as a primary electron along said separating distance by means of its corresponding electric field so that said gas electron multiplier operates as an amplifier having a gain which is the product of the gain yield from each successive matrix.

14. The radiation detector of claim 1, wherein said collecting electrode comprises, on an insulator foil:

a first set of elementary anodes disposed on a first face of said insulator foil, said first face of said insulator foil and said first set of elementary anodes facing said gas electron multiplier, said first set of elementary anodes comprising a plurality of parallel electric conductive strips extending along a first given direction;

a second set of elementary anodes disposed on a second face of said insulator foil, said first and second sets of elementary anodes being separated by said insulator foil, said second set of elementary anodes comprising a plurality of parallel electric conductive strips extending along a given direction, transverse to said first given direction, and

said first and second sets of elementary anodes thereby enabling detection of said electron avalanche along said second and first directions, respectively, so as to form a bidirectional radiation detector.

15. In a radiation detector in which primary electrons are released into a gas by ionizing radiations, said radiation detector comprising a drift region from which said primary electrons are caused to drift by means of a substantially parallel electric field, a collection region, a gas electron multiplier located between said drift region and said collection region and comprising at least one matrix of electric field condensing areas, said electric field condensing areas being distributed within a solid surface which is substantially perpendicular to said parallel electric field, each of said condensing areas producing a local electric field amplitude enhancement to generate in said gas an electron avalanche from one of said primary electrons such that said gas electron multiplier operates as a preamplifier of given gain for said primary electrons upstream said collecting electrode of said radiation detector, and a collecting electrode for collecting from said collection region electrons produced by said electron avalanche, said matrix of electric field condensing areas comprising:

an insulator having first and second metal claddings on opposed faces thereof so as to form a planar sandwich structure;

a plurality of through holes extending transversely through said planar sandwich structure; and

biasing means for providing a bias voltage which is applied to said first and second metal claddings so as to generate at the level of each of said through holes one of said electric field condensing areas.

16. The gas electron multiplier of claim 15, wherein said local electric field amplitude enhancement generated by each of said condensing local areas is substantially symmetrical in relation to an axis of symmetry of said condensing local area which is perpendicular to said plane so that said local electric field amplitude enhancement is at a maximum at the center of symmetry of said condensing local area.

17. The gas electron multiplier of claim 15, comprising a plurality of successive matrices of electric field condensing areas, said successive matrices being disposed parallel to one another and two successive matrices of said successive matrices being spaced apart from each other by a given

separating distance in a direction parallel to said parallel field forming a first parallel electric field so as to define therebetween successive electric fields and to allow any electron of one electron avalanche to drift as a primary electron along said separating distance by means of its corresponding parallel electric field such that said gas electron multiplier operates as a preamplifier the gain of which is the product of the gain yield from each successive matrix upstream of said collecting electrode of said radiation detector.

18. A radiation detector in which primary electrons are released into a gas by ionizing radiations, said radiation detector comprising a drift region from which said primary electrons are caused to drift by means of an electric field, a collection region, a gas electron multiplier located between said drift region and said collection region and comprising at least one matrix of electric field condensing areas, said electric field condensing areas being distributed within a solid surface which is substantially perpendicular to said electric field, and a collecting electrode for collecting electrons from said collection region said matrix of electric field condensing areas comprising:

an insulator having metal cladding on opposite faces thereof forming a sandwich structure; and

a plurality of through holes extending transversely through said sandwich structure, each of said through holes having an opening aperture diameter comprised between 20 μm and 100 μm.

19. The radiation detector of claim 18, wherein said insulator foil is made of a polymer material of thickness comprised between 25 μm and 500 μm, said through holes being spaced apart from one another at a distance comprised between 50 μm and 300 μm.

20. The radiation detector of claim 18, wherein each through hole of said plurality of through holes is provided with an internal lateral surface delimited by said insulator, said lateral surface comprising at least one local zone in which permanent electric charges are implanted, said permanent electric charges being distributed within said insulator and local zone thereof so as to further enhance and stabilize said electric field at the level of each corresponding electric field condensing area.

21. The radiation detector of claim 18, wherein each through hole of said plurality of through holes is provided with an internal lateral surface delimited by said insulator, said lateral surface comprising at least one local zone of electric conductivity comprised between 10^{15} and 10^{16} Ω/square.

22. The radiation detector of claim 18, wherein each said through hole of said plurality of through holes has a cross section along a longitudinal plane of symmetry of said through hole which is conical in shape, each of said through holes comprising first and second circular openings of given values different from each other thereby forming first and second opening aperture diameters of different values, said radiation detector further comprising controllable direct and reverse biasing means for providing a direct biasing voltage and a reverse biasing voltage, respectively, which are applied to said first and second metal claddings so as to generate at the level of each of said through holes one of said electric field condensing areas which is thus functionally reversed.

23. A radiation detector for photons emitted by an external source, said radiation detector comprising, in a vessel containing a gas adapted to generate an electron avalanche from a primary electron through an electric field:

an inlet window having an inner face and a transparent electrode disposed on the inner face of said inlet window, said inlet window and transparent electrode being adapted to transmit said photons within said gas;

a photocathode layer facing said transparent electrode, said photocathode layer being adapted to generate one photo-electron as a primary electron under impingement of each one of said photons thereon;

a gas electron multiplier comprising at least one matrix of electric field condensing areas, said matrix of electric field condensing areas comprising:

first and second foil metal-clad insulators on opposed faces of said matrix comprising first and second metal claddings and first and second insulators, said photocathode layer being disposed on said first metal cladding so as to face said transparent electrode, said photocathode layer, and said first and second metal claddings, forming a sandwich structure with said first and second insulators, and

a plurality of through holes traversing said sandwich structure such that each of said through holes permits free flowing therethrough of the gas and any electrically charged particle generated therein;

first biasing means for maintaining said transparent electrode and first metal cladding substantially at the same voltage value so as to allow extraction of any photo-electron generated by said photocathode layer under impingement thereof of each one of said photons;

second biasing means for providing a bias voltage which is applied between said first and said second metal claddings, so as to form, at the level of each of said through holes, one of said electric field condensing areas in which a condensed electric field is generated so that said condensed electric field operates to convey each of said photo-electrons to one given electric field condensing area and to then generate from said photo-electron regarded as a primary electron one electron avalanche which is passed through said through hole forming said given electric field condensing area;

a collecting electrode comprising a plurality of elementary anodes, said collecting electrode facing said second metal cladding and being spaced apart therefrom, so as to define a detection region within said vessel; and

third biasing means for providing a bias voltage which is applied to said collecting electrode so as to allow the detection of said electron avalanche.

24. The radiation detector of claim 23, wherein said collecting electrode comprises, on an insulator foil:

a first set of elementary anodes disposed on a first face of said insulator foil, said first face of said insulator foil and said first set of elementary anodes facing said gas electron multiplier, said first set of elementary anodes comprising a plurality of parallel electric conductive strips extending along a first given direction

a second set of elementary anodes disposed on a second face of said insulator foil, said first and second sets of elementary anodes being thus separated by said insulator foil, said second set of elementary anodes comprising a plurality of parallel electric conductive strips extending along a given direction, transverse to said first given direction,

said first and second sets of elementary anodes thereby enabling detection of said electron avalanche along said second and first directions respectively so as to form a bidirectional radiation detector.

25. A radiation detector in which primary electrons are released into a gas by ionizing radiations, said radiation detector comprising a drift region from which the primary electrons are caused to drift by means of an electric field, a collection region, a gas electron multiplier located between said drift region and said collection region, said multiplier comprising a sandwich structure comprising an insulator having first and second conductive surfaces on opposite sides thereof and a plurality of through holes extending transversely through said sandwich structure to form a matrix of electric field condensing areas, each of said electric field condensing areas producing a local electric field amplitude enhancement sufficient to generate in said gas an electron avalanche from any of said primary electrons in said drift region and to transfer multiplied electrons into the collection region, and a collecting electrode for collecting from said collection region multiplied electrons produced by said electron avalanche.

26. A radiation detector in accordance with claim 25, wherein a plurality of gas electron multipliers are disposed between said drift region and said collecting electrode.

* * * * *

US006429578B1

(12) United States Patent
Danielsson et al.

(10) Patent No.: US 6,429,578 B1
(45) Date of Patent: Aug. 6, 2002

(54) DIAGNOSTIC AND THERAPEUTIC DETECTOR SYSTEM FOR IMAGING WITH LOW AND HIGH ENERGY X-RAY AND ELECTRONS

(76) Inventors: Mats Danielsson, Stockholmsvägen 45 A, S-182 78, Stocksund; Anders Brahme, Långbackavägen 22, S-182 33, Danderyd, both of (SE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: 09/236,596

(22) Filed: Jan. 26, 1999

(51) Int. Cl.^{7} H01J 43/00

(52) U.S. Cl. .... 313/105 CM; 313/103 CM; 313/105 CM; 250/374; 250/385.1

(58) Field of Search .... 313/542, 544, 313/103 R, 103 CM, 105 R, 365, 523, 532, 533, 538; 250/211 VT, 214 VT, 374, 385.1

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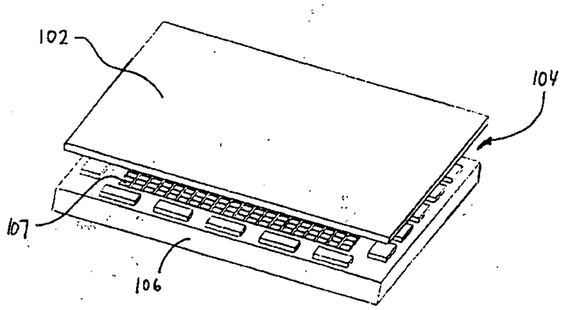
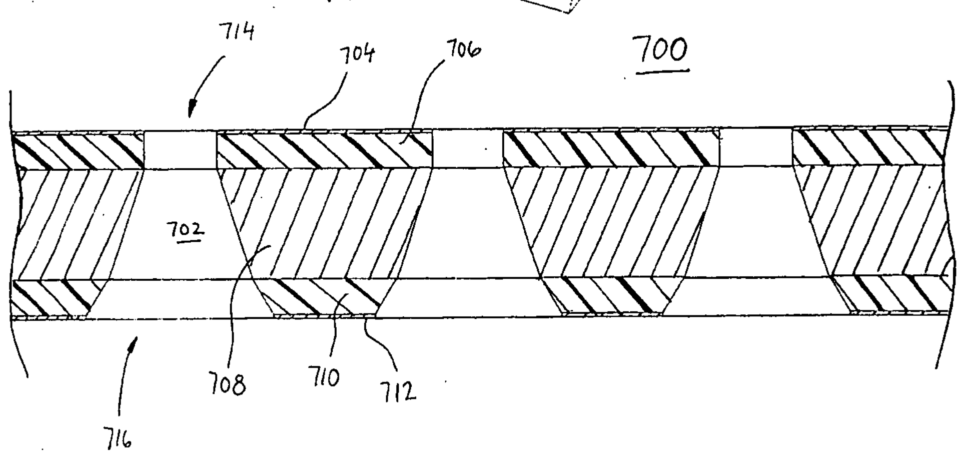
Primary Examiner—Michael H. Day
Assistant Examiner—Joseph Williams
(74) *Attorney, Agent, or Firm*—Young & Thompson

(57) ABSTRACT

A detector unit for detecting photons in the energy range 1 keV to 100 MeV, includes at least two converter layers adapted to interact with incident X-ray photons and to cause electrons to be emitted therefrom, at least one amplifier adapted to interact with the electrons emitted from the converters and adapted to produce a multiplicity of secondary electrons and photons representing a signal proportional to the incident fluence of X-ray photons, a connector connecting the detector to an electric field generator providing an electric drift field for secondary electrons in the detector, and a sensor device arranged to receive the signal and provide an input to electronic signal processor.

23 Claims, 9 Drawing Sheets





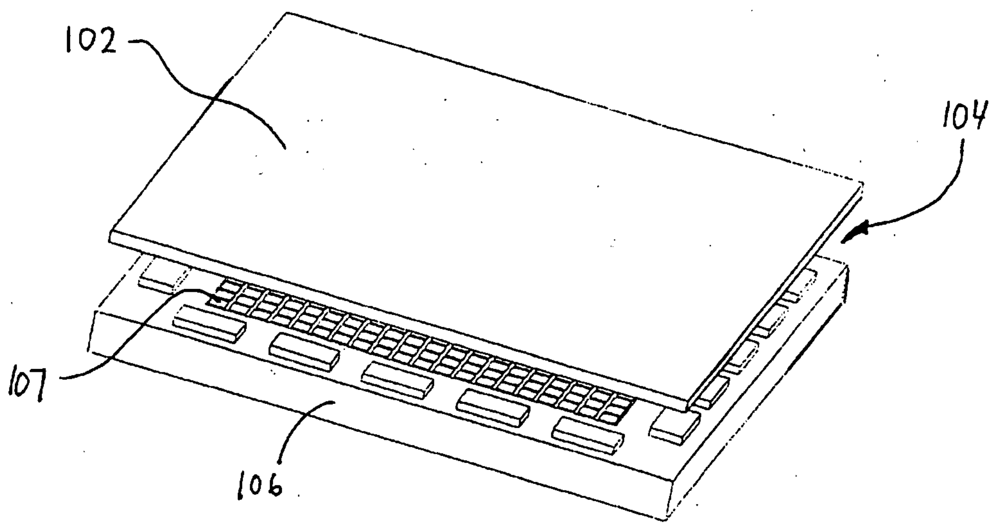


Fig. 1a

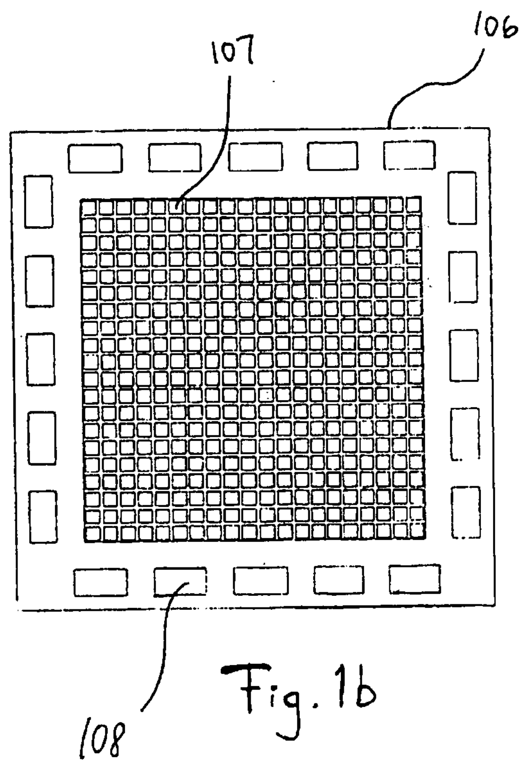


Fig. 1b

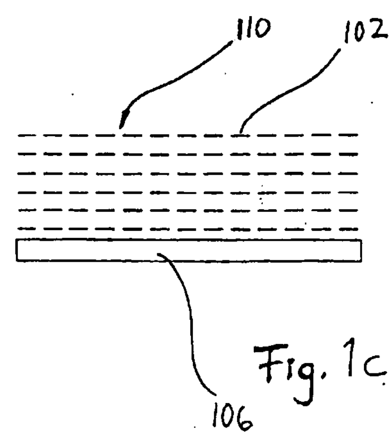


Fig. 1c

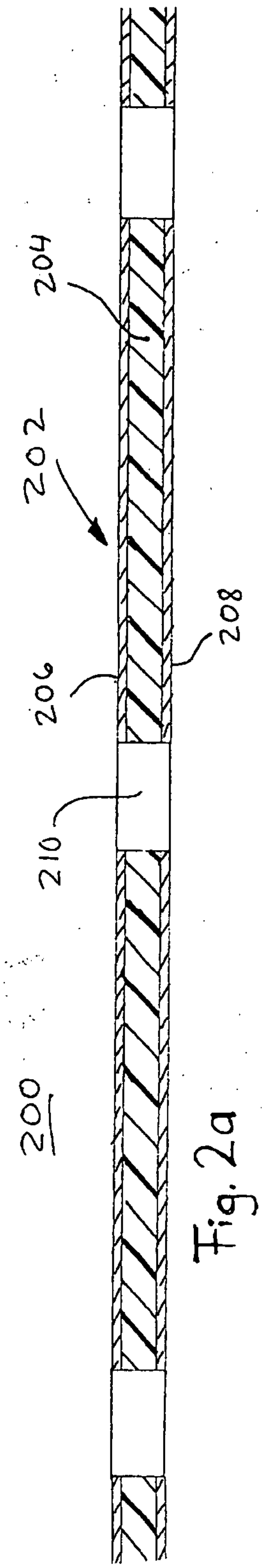


Fig. 2a

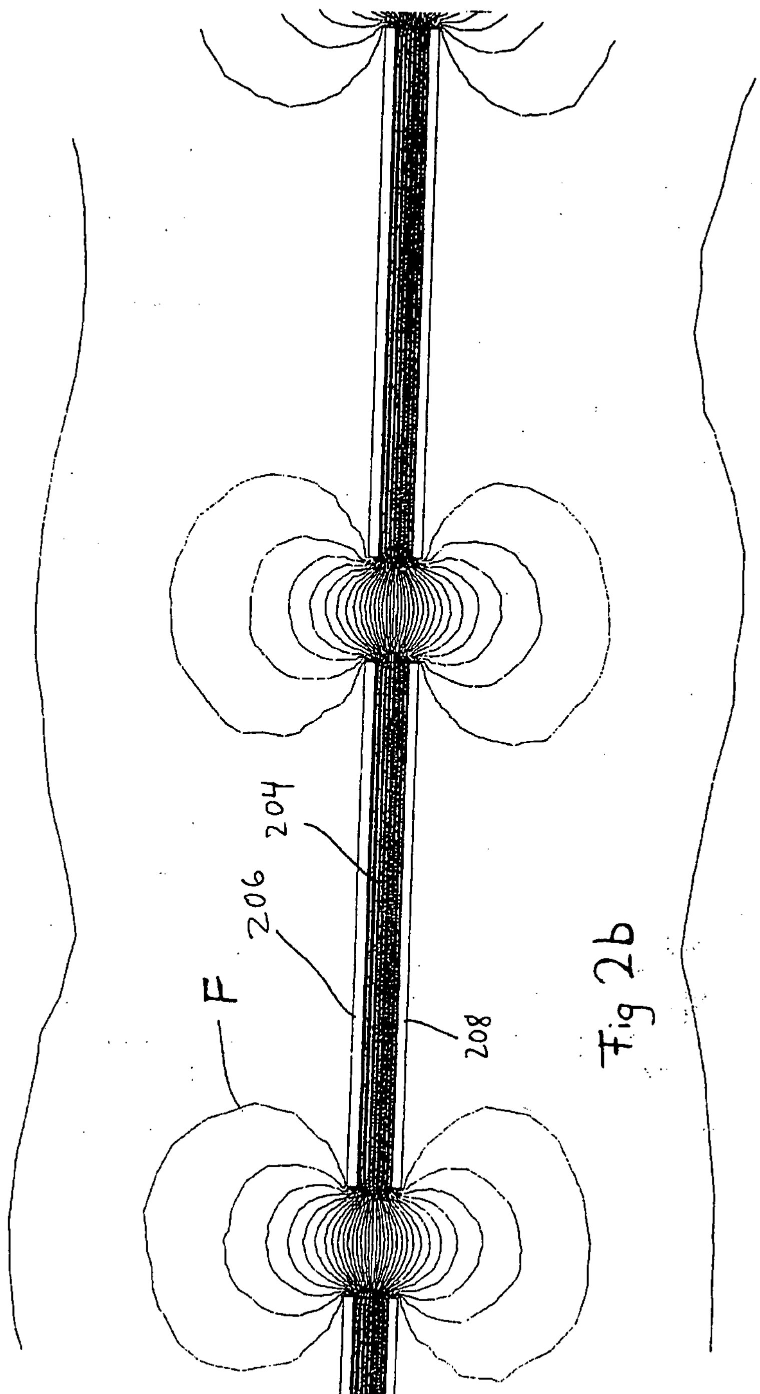
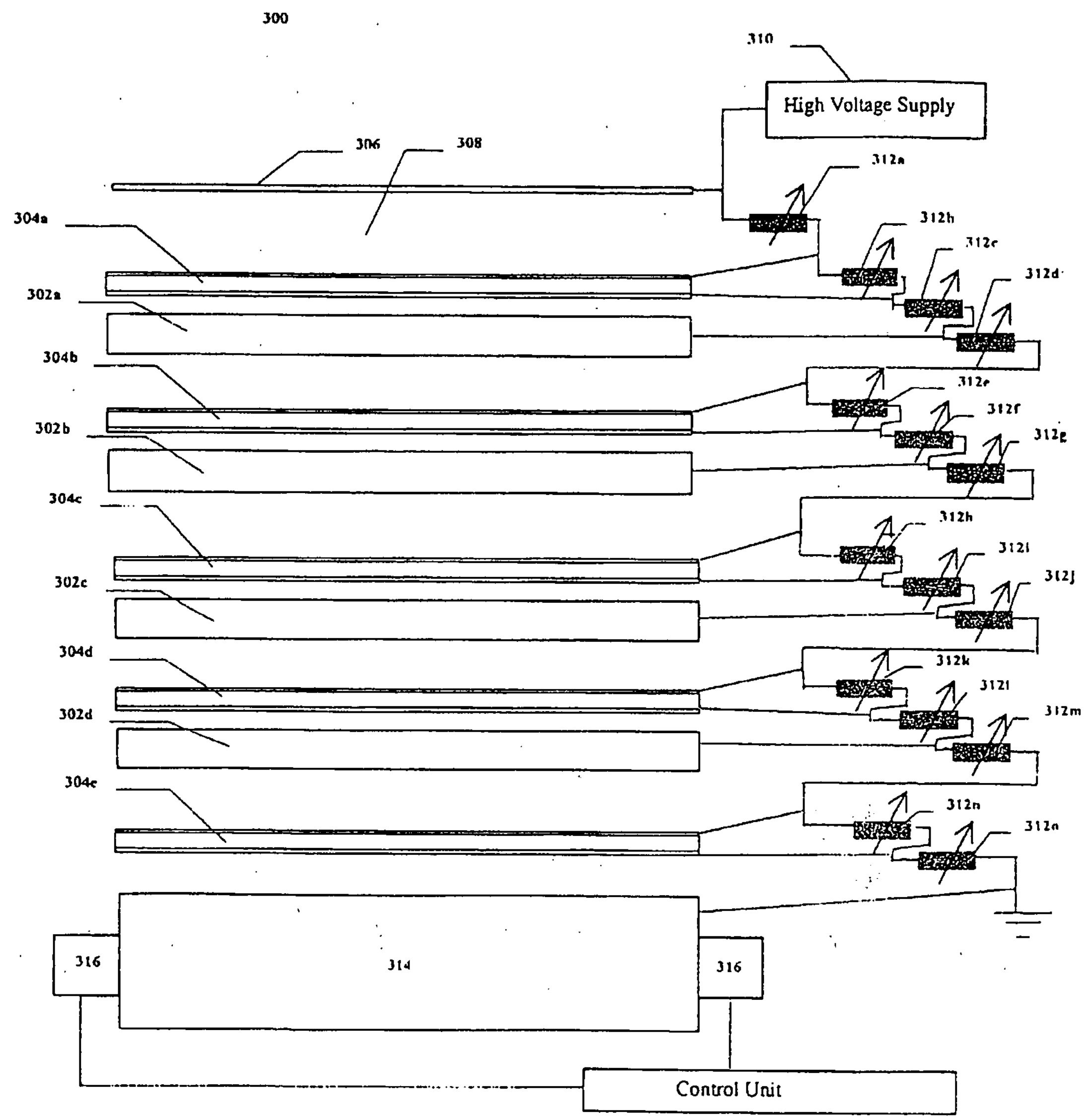


Fig 2b


300
310
High Voltage Supply
306
308
312a
304a
312b
312c
302a
312d
304b
312e
312f
302b
312g
304c
312h
312i
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312o
316
314
316
Control Unit

Fig. 3

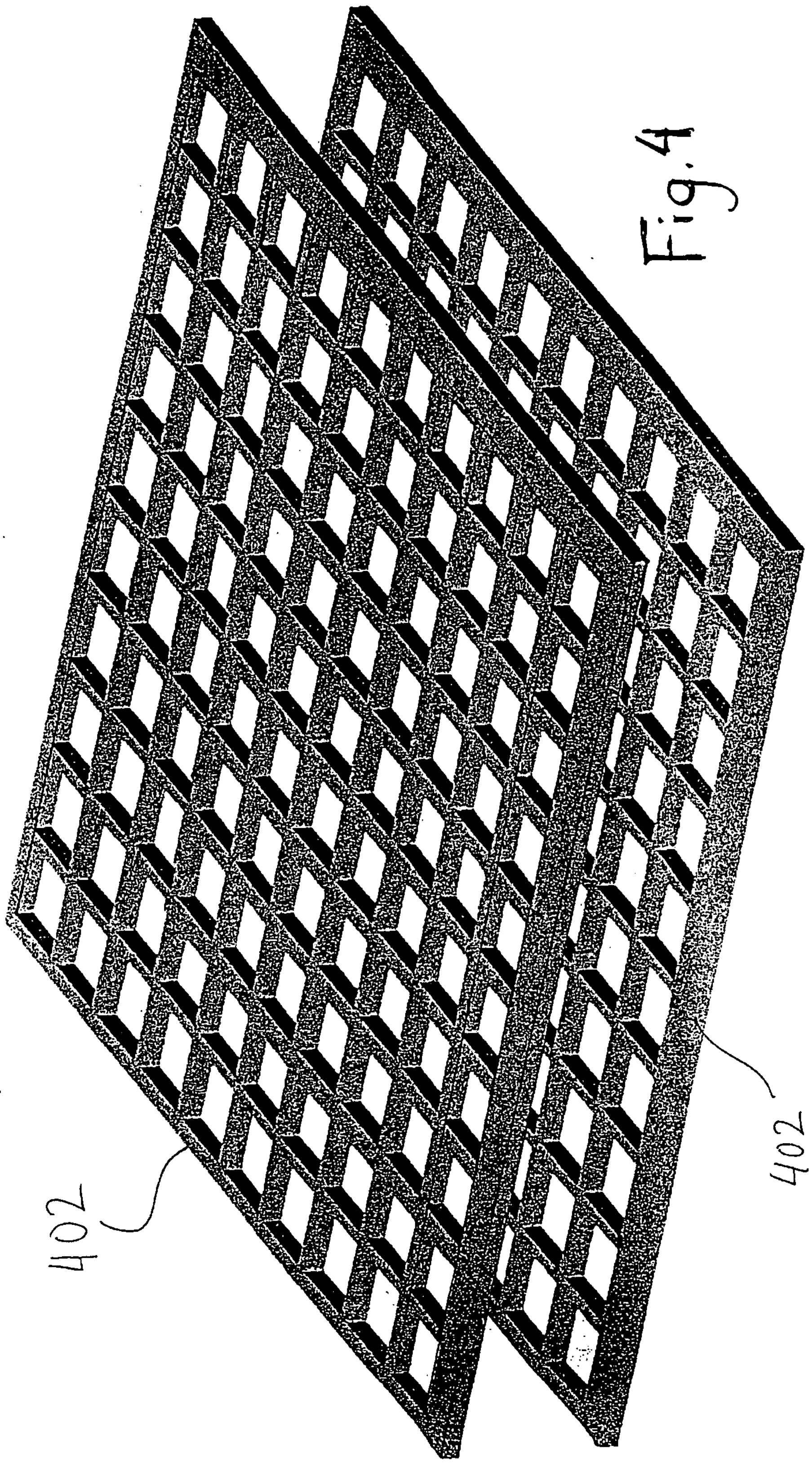


Fig. 4

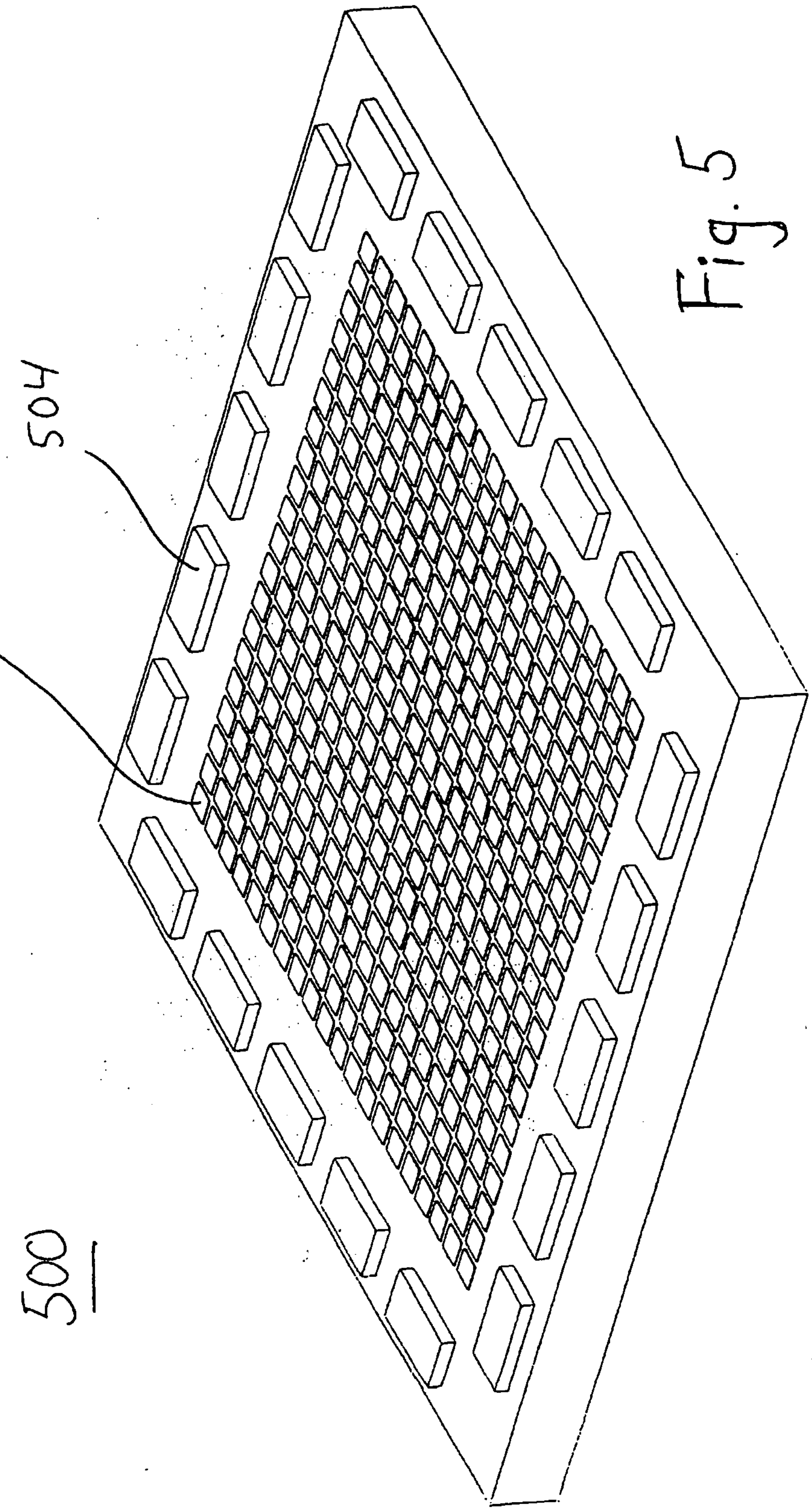
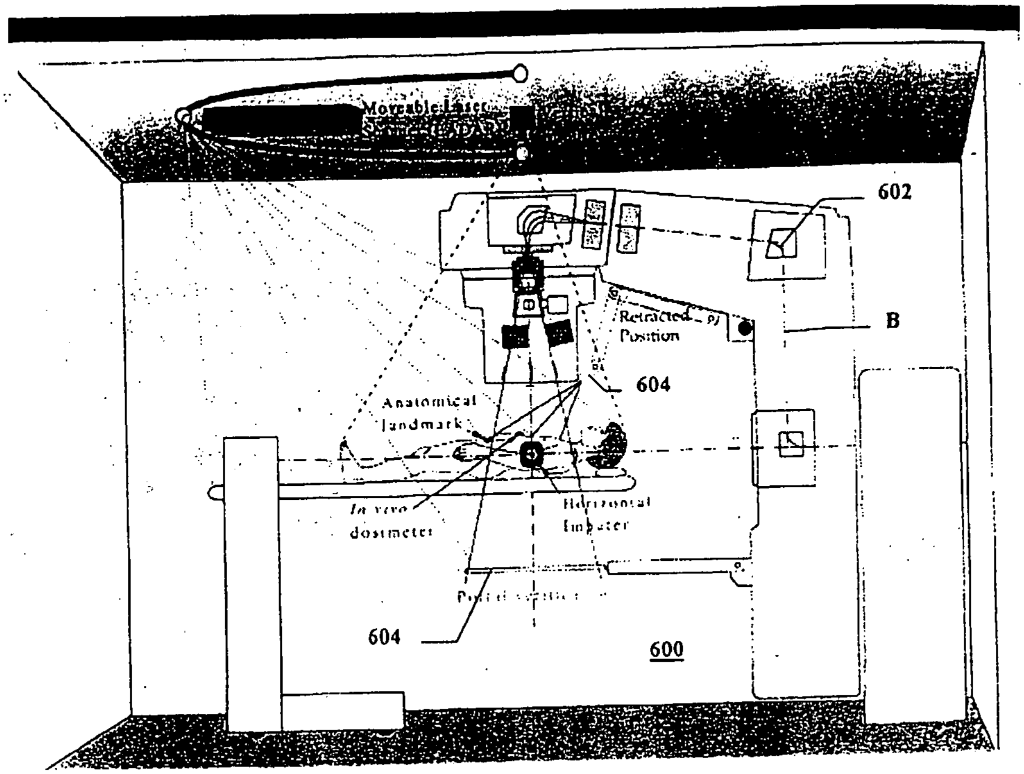
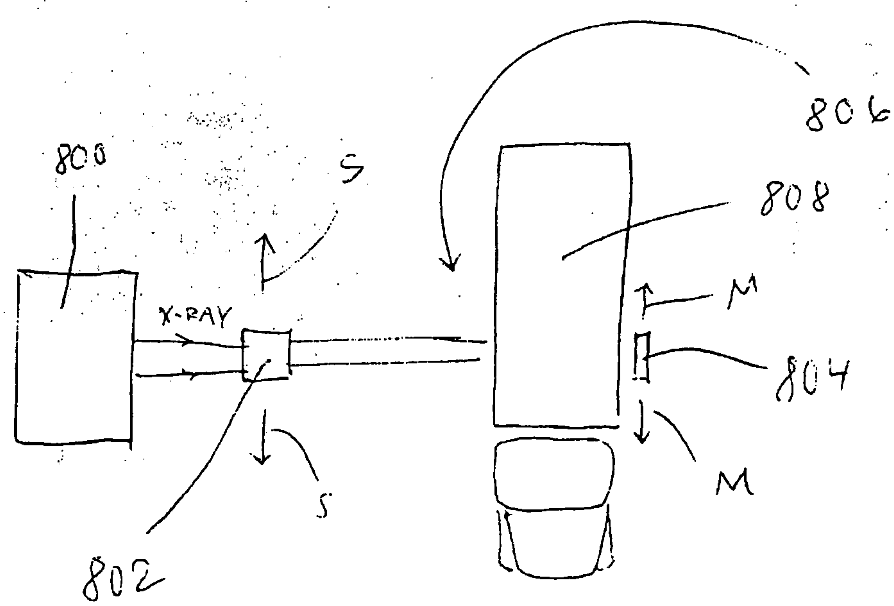


Fig. 5



Moveable Laser
602
Retracted Position
B
604
Anatomical landmark
In vivo dosimeter
Horizontal Imager
604
600

Fig. 6



806
800
S
808
X-RAY
M
804
M
S
802

Fig. 8

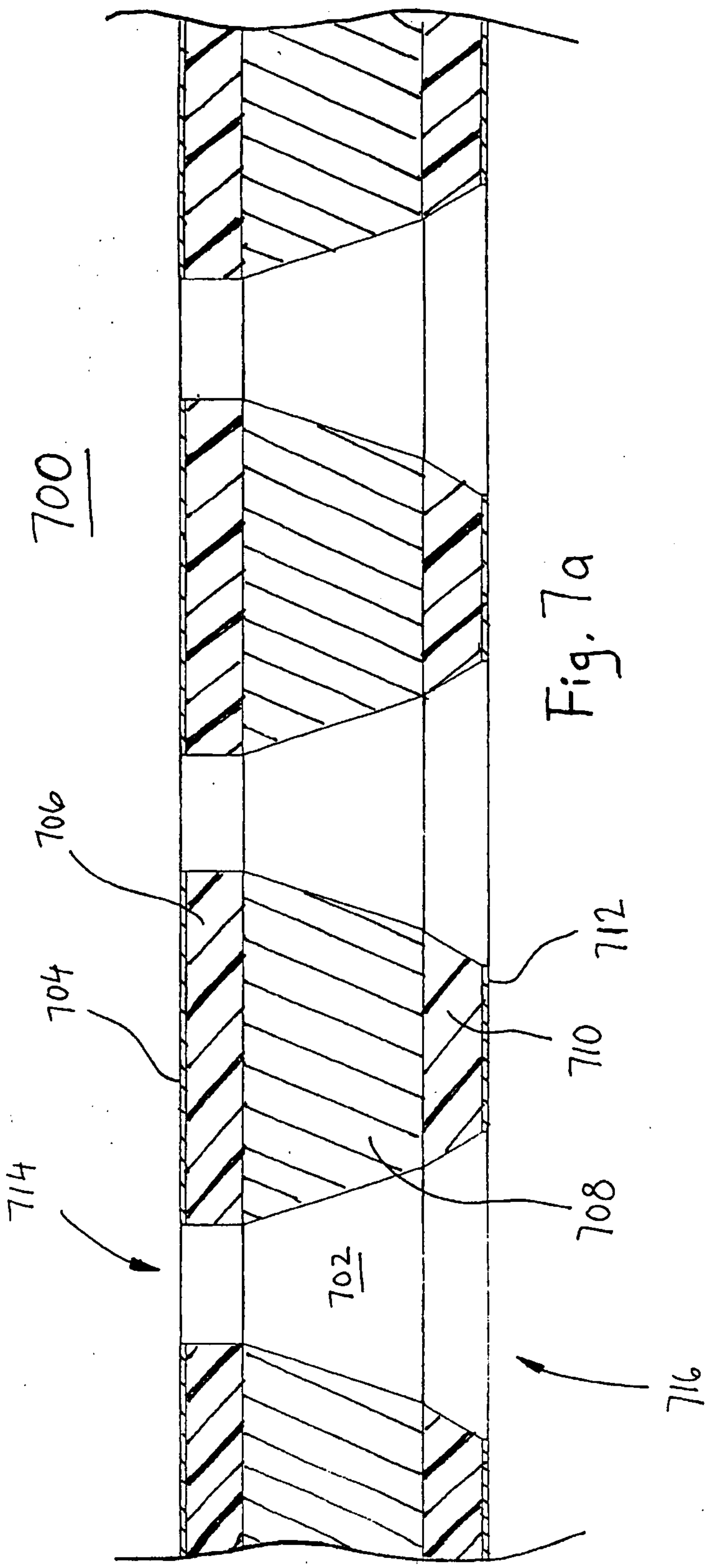


Fig. 7a

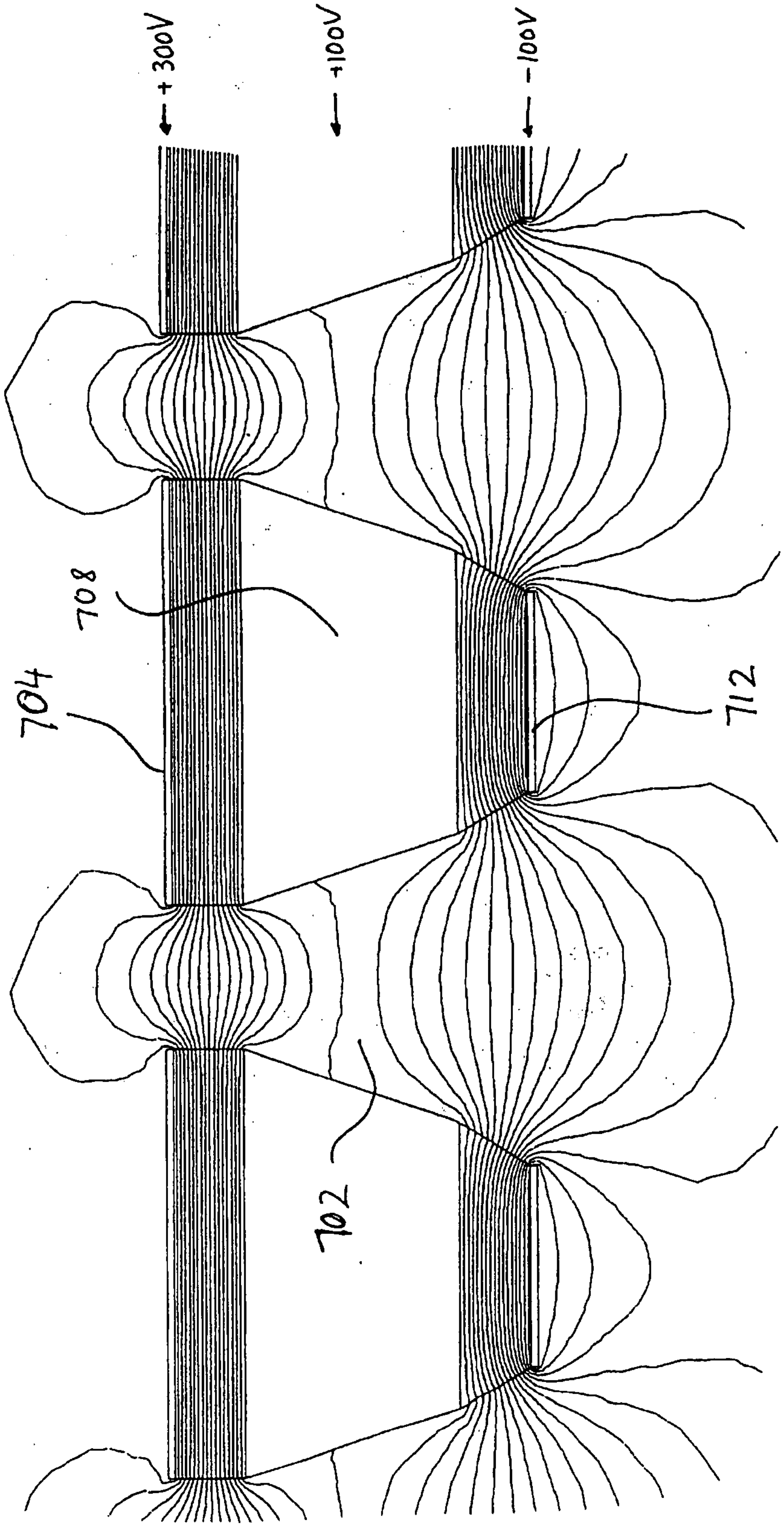
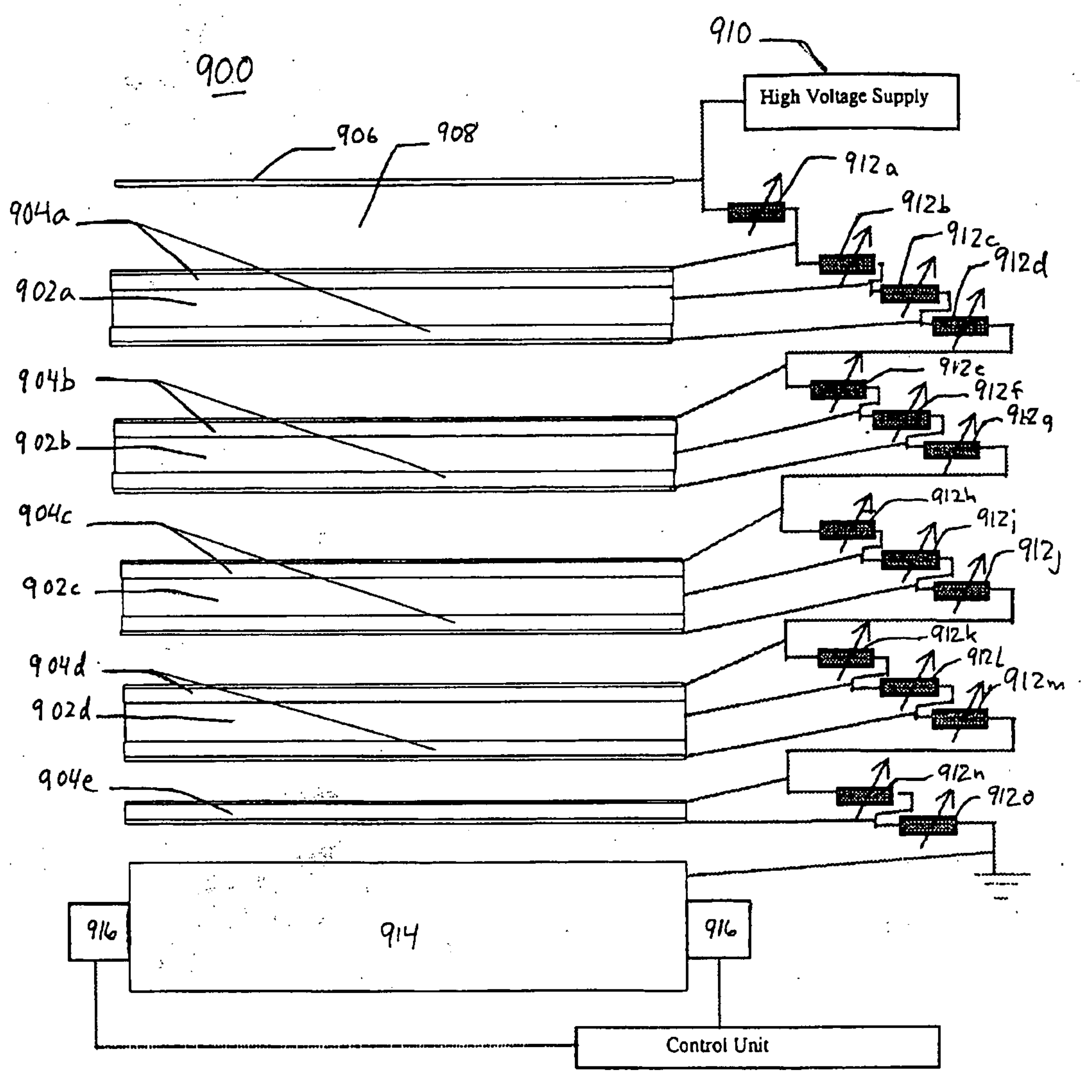


Fig. 7b



910
High Voltage Supply
900
906
908
912a
912b
912c
912d
904a
902a
904b
902b
912e
912f
912g
904c
902c
912h
912i
912j
904d
902d
912k
912l
912m
904e
912n
912o
916
914
916
Control Unit

Fig. 9

DIAGNOSTIC AND THERAPEUTIC DETECTOR SYSTEM FOR IMAGING WITH LOW AND HIGH ENERGY X-RAY AND ELECTRONS

The present invention relates to a general X-ray and electron imaging device, particularly useful for verification, control and optimization of radiation treatment of cancer as well as for applications like diagnostic X-rays, non-destructive testing and screening of containers and vehicles in airports and in customs. More particularly it relates to a detector system with high efficiency over a wide range of photon and electron energies, from diagnostic X-rays starting from the low energies of a few keV all the way up to a hundred MeV, i.e. energies that are of interest and used in radiation therapy or for imaging of large and/or dense objects.

BACKGROUND OF THE INVENTION

Real time electronic detectors have during the last 30 years revolutionized many areas of X-ray imaging. This includes diagnostic modalities like computed tomography for detailed imaging of the human head and body as well as image intensifiers and video techniques for imaging of the cardiovascular system and for airport security. There are several advantages with real time electronic detectors including improved detection efficiency, wider dynamic range and instantaneous response. Digital images also allow immediate display, electronic storage, diagnosis through telecommunication and computer-aided detection, on-one image enhancement and diagnosis. In spite of the obvious advantages with digital imaging it has turned out to be very hard to replace current film-screen combinations in applications demanding high spatial resolution over large areas, in particular when constraints like high tolerance to radiation damage and reasonable cost are added. Despite its advantages film has a number of disadvantages such as low efficiency, limited dynamic range, noise and the need for chemical development.

The working principle of the present range of electronic detectors is that photons transmitted through the irradiated object are converted to electrons through electromagnetic interactions. Those electrons are in some devices collected directly by dedicated sensors or they are guided through some fluorescent material where secondary light is created and this light is in turn detected by a sensor like e.g. a CCD. In imaging devices for higher X-ray energies, a special converter is added in front of the detector to increase the probability for electromagnetic interaction of the X-rays. This is needed to increase the efficiency of the devices since higher energy X-rays are much more penetrating and would otherwise pass the detector undetected. The converter is usually made as a thin plate of some heavy metal like copper or iron, but molybdenum, chromiun or tungsten are equally suitable. In principle any material could be used, but the efficiency of the device will increase with increasing atomic number. Thus, an atomic number greater than 20 is preferable.

For the purpose of this application the term "electromagnetic interactions" should be taken to encompass all physical interactions between photons and matter that causes generation of at least an electron, i.e. via Compton effect, pair-production or photo electric effect.

The term "conversion" is meant to encompass any process involving a photon, wherein some or all of the energy of that photon is transferred to some other corpuscle and wherein a

free electron is produced as a result of said energy transfer. Thus, a "converter" is any device capable of producing this effect. It could simply be a gas enclosed in a volume, wherein incident photons interact with the gas in the photoelectric effect to produce electrons. It can also be a sheet or other type of structure of a solid material, in which electrons are generated via the Compton effect or by pair production (electron—positron generation).

"Amplification" is to be construed as a process where one electron interacts with atoms or molecules of a gas thereby causing ionization thereof to produce a plurality of electrons and "holes" (positive gas ions). Thus, "amplification" is meant to encompass both primary ionization regardless of whether there is an electric field present or not, as well as the well known avalanche fenomenon that occurs in electric fields of the order of 10^4 V/m or more.

Thus, an "amplifier" will encompass any structure that causes such "amplification" it could e.g. simply be a gas enclosed in a volume where incident electrons will interact with the gas, or a more complex device where an electric field is generated.

Radiation therapy and surgery remain the main modalities for cancer cure in the industrialized world. Radiation therapy is used for more than half of the new cancers with permanent eradication of the tumor without severe complications in more than half of the cases. The radiation dose is delivered to the patient in different fractions, one fraction a day over a period of a couple of weeks. Alignment of the radiation field relative to the tumor is of paramount importance. The alignment has to be particularly accurate when intensity modulation is used and the tumor is close to sensitive organs like the spinal cord. Positioning errors should by no means exceed 2 to 5 mm depending on treatment site. Monitoring and controlling the treatment with a detector behind the patient is usually referred to as portal imaging. More recently, it has been shown that a correction of the patient set-up using the information from an Electronic Portal Imaging Device (EPID) increases the probability of a complication free tumor cure in the order of 10%. However, as already indicated, film still remains the most common tool for verification and quality control of the treatment and is used in more than 90% of the cases. The EPID's has proven valuable since digital images allow electronic storage and processing of the data. They also in principle enable an on-line control and verification of the treatment even if this is difficult because of the low efficiency of the present EPID's and the corresponding relatively long times for data acquisition. They also facilitate an adaptive real time control during the course of delivery of the different fractions of the treatment. In portal imaging, it is obvious that the detectors need to be highly radiation tolerant and this is a severe constraint one has to take into account when designing the detector.

There are two main types of EPID systems available commercially today: One is a mirror-based video system and the second is an electronically scanned liquid-ionization chamber system. In both cases, the incident photons are converted to electrons with an efficiency of about 5%–8% through interactions in a metal plate, typically 1.5 mm of copper. If the metal is made thicker, scattering of the electrons in secondary reactions is becoming a problem and electrons will stop in the metal. The typical range for 1 MeV electrons in Cu is less than 0.7 mm. This range is approximately proportional to the energy of the electrons. This puts a fundamental limit on the obtainable efficiency for these devices. Both approaches have proven valuable in localizing the patient in the radiation field and verification of the

radiation therapy. A major drawback is that the contrast and quality of the resulting images only makes the bone structure visible and not internal organs and the tumor itself, the exact position of these organs remains unknown. The only way of being sure about these positions would be diagnostic X-ray images taken with the patient in the actual treatment position, without movement of the patient and right before the actual treatment starts since any movement would cause change in position of the internal organs. Unfortunately existing EPID's are almost insensitive to X-rays of diagnostic energies.

The main specific drawback with the video system is its low efficiency due to loss of photons in the process of de-magnifying the fluorescent screen through a mirror, lens or fiber optic taper to the camera. This efficiency is in fact less than 0.01%. Another problem is the inherent bulkiness of the system that may hamper patient set-up and make them difficult to use in machines with beam stoppers to stop the radiation beam after passing the patient.

In the liquid-ionization chamber the pixels are scanned by a switched high voltage one row at a time and the currents from the pixels are read out by a row of 256 electrometers, the whole detector consist of an array of 256x256 pixels with a spacing of 1.27 mm. This generates a current of typically 50 pA and the noise is around 0.5 pA. The liquid is integrating the created charge for around 0.5 s and it takes around 5 s to get an image. The drop in efficiency due to the scanning is thus a factor 10. Limitations are long-time stability of the ultra-clean liquid and pick-up due to the high-voltage switching.

The most promising emerging EPID seems to be amorphous silicon arrays. They have been developed since around 1990 but are not yet a commercial product. Advantages compared to the video system are much better optical coupling (around 50%) between the fluorescent screen and the detector since the array is positioned in close proximity to the screen and there is no demagnification. Each pixel is controlled by an a-Si transistor, one row of pixels is gated at a time, and the accumulated charge is amplified by a row of preamplifiers and digitized by a 12 bit ADC. Amorphous silicon has the advantage that it can be deposited over large areas but is not ideal for fabrication of transistors; the ON resistance usually exceeds mega-ohms and this slows down the readout of the charge. In spite of enormous investments from the flat-panel display industry it is not trivial to manufacture large arrays without defects and the cost for a large instrumented a-Si array for X-ray imaging (~25x25 cm^2 size) is very high. The efficiency is also for this device limited by the fact that only 6%–8% of the incident photons interacts at all in the detector.

The trend in radiation therapy is towards conformal intensity modulated treatments and hyperfractionation that reduces the dose per treatment field. This increases the demands on the EPID in terms of efficiency, high quality image for alignment checks should be obtained at dose levels of 0.01 Gy corresponding to an image acquisition time of 0.25 s at a dose rate of 2 Gy per minute. For a total dose for the field of 1 Gy this means the treatment maybe aborted at radiation levels of less than 1% of the single field dose in case of misalignment. The intended set-up may be documented through either a simulator or a digitally reconstructed radiograph (DRR), which has been reconstructed for a certain beam set-up using computed tomography. Potentially this will enable computer-aided on-line detection of misalignments of the radiation field.

If one compares the EPID to for example an upgrade in accelerator equipment for the treatment unit the cost for an EPID would be less than 0.15 M$ while a new accelerator would cost about 2 MS. Since a portal imager would have very significant impact on estimated benefits for the patient in terms of increased probability of eradicating the tumor, it is in reality a very cost-effective device compared to other investments. If the effect on the outcome of the treatment is 10%, this corresponds to about 1,5 million more patients saved in the U.S. per year.

SUMMARY OF THE INVENTION

Thus, there is still a strong need in this field for a detection means that allows an adaptive real time control during the course of delivery of radiation during treatment. In addition, it would be advantageous if the same detection system could be used for both low and high-energy photons, such that for quality control purposes in medical care, a high quality image could be obtained before therapeutic irradiation begins. Furthermore, it would be advantageous if there need be no physical shift or replacement of the detection unit between high and low energy detection, i.e. the detector units should not need to be moved or damaged due to exposure to high energy radiation.

These objects are achieved with a device, method and system as defined in the appended claims.

In particular the present invention in a preferred embodiment concerns detectors comprising a plurality of amplifier and converter stages.

The spatial resolution is determined by the pixel pitch, which will be around 1 mm in the prototype detector, but could be taylored to suit the application in question. This is not a very competitive resolution for diagnostic medical imaging but is sufficiently high for portal imaging. The portal imager according to the invention will also be used as a detector for diagnostic X-rays. It may not be the optimum detector for this task but it will provide valuable additional high-contrast images to correct for internal displacements of sensitive organs as well as the target with the patient in the actual treatment position. To use separate X-ray detectors for all these tasks is impractical. With some modifications the system can also be used for precision dosimetry and current mapping of therapeutic radiation fields. It can thus be used to optimize the dose delivery with different radiation treatment units and techniques.

A particular advantage with a preferred embodiment of the detection system according to the present invention is that it allows the contrast of images produced to be optimized to a high degree and also makes it possible to determine the elemental composition of different parts of the object. This is achieved by the provision of gain control for each individual amplifier in the stack, whereby detection of photons can be discriminated between high and low energies.

Further advantages with the invention are:

1) Possibility of an order of magnitude higher efficiency compared to present detectors for high energy X-rays due to use of multiple conversion layers in combination with efficient collection of the signals from each conversion layer. The integral signals from all the individual layers are detected by one single matrix of sensors.

2) A high signal to noise ratio due to the amplification of the signal in the gas.

3) High radiation resistant since no active electronics need to be directly exposed to the beam, if desired.

4) Very fast parallel read-out enabling acquisition of the whole image matrix in less than 3 ms, if desired.

5) The energy response of the detector can be changed simply by altering the potential on the different electrodes.

6) Rugged design where the amplification is geometrically stable but adjustable.

7) Highly efficient over a wide range of energies. This enables the combination of an detector for diagnostic and therapeutic X-rays in one single device by using a thin entrance window and gas volume on top of the first converter layer. If a diagnostic X-ray tube is inserted above the patient a high contrast diagnostic X-ray image could be obtained right before the treatment starts and thus the exact position of any organs and the tumor itself could be determined.

8) Energy sensitive if desired. This makes it possible to optimize the contrast for any given imaging task and also opens the possibility to determine the elemental composition of the object. This energy sensitivity also enables dual-energy imaging in the sense that it is possible to determine not only the X-ray attenuation in the object but also the different elements the object consist of by comparing images with different weighting of low and high energy X-rays.

9) The invention also offers the possibility to weight the information from X-rays of different energies in such a way that the contrast in the resulting image is optimized for the object of interest.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1*a* is a perpective view of a basic embodiment of a detecor according to the invention;

FIG. 1*b* is a schematic top view of a charge collector according to the invention;

FIG. 1*c* is a schematic side view of a stack of converters on top of a charge collector;

FIG. 2*a* is a schematic view of a GEM structure suitable for use with the invention;

FIG. 2*b* shows equipotential lines for a biased structure as shown in FIG. 2*a;*

FIG. 3 is a schematic overview of a preferred embodiment of a detector unit according to the invention;

FIG. 4 is a perspective view of an embodiment of the detector comprising a mesh structure;

FIG. 5 is a perspective view of a charge collector according to the invention;

FIG. 6 schematically shows a set-up for radiation therapy;

FIG. 7*a* illustrates an alternative structure for a further embodiment of the detector according to the invention;

FIG. 7*b* shows schematically equipotential lines for biased structure of FIG. 7*a;*

FIG. 8 illustrates schematically a set-up for cargo screening; and

FIG. 9 is a schematic overview of still another preferred embodiment of a detector unit according to the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The basic principle behind the invention will now be described with reference to FIGS. 1*a* and *b* showing the most general embodiment of a detector according to the invention.

This figure shows an X-ray to e converter **100** in the form of a sheet **102** of a heavy metal, e.g. Cu, about 1.5 mm thick. Below this converter there is an air gap **104** of about 1 mm, and at the bottom there is a multi-layer PCB **106** (Printed Circuit Board) (described more in detail with reference to FIG. **5** below). Briefly it comprises pads **107***b*, 1 mm^2, distributed over the surface of a polymer board, and connected to ASIC inputs **108** positioned at the edges of the PCB (see FIG. 1*b*).

X-rays on the converter sheet **102** will generate electrons in the metal, exiting into the air gap **104**. The negatively charged electrons will ionize the gas, and the electron signal will be amplified through an avalanche in the gas if the field in the gap **104** is 10^4 V/m or higher. The secondary electrons will be collected on the electrode pads at ground potential. If there is a gas volume above the converter sheet **102** and the top cover (not shown) is made essentially transparent to diagnostic X-ray energies, the device can be used as a detector for diagnostic purposes too. This requires that the converter **102** be perforated such that the electrons can be drifted through the holes **110**. In addition to

If several converters are stacked the efficiency will be increased. This is shown schematically in FIG. 1*c*. By applying an appropriate voltage across the stack and by selecting the thickness and hole diameter appropriately for the converter sheets, it is possible to obtain avalanche amplification in the holes **110** in the perforated converter sheets **102**.

Another way of achieving amplification is to provide a separate amplifier device. Several such devices are known, and one type is designated Gas Electron Multipliers (GEM).

Referring now to FIG. 2*a* there is shown the main component of such a GEM, generally designated **200**. It is a thin composite mesh **202** acting as proportional avalanche amplifier in gas counters (U.S. patent pending, Sauli et al).

The mesh consists of a thin insulating foil **204**, e.g. of Kapton®, which is metal-clad **206**, **208** on both sides, a suitable metal being Cu, and perforated by a regular matrix of holes **210**. The holes may be 100 μm wide. The insulating foil **204** may be 50 μm thick, the thickness of the metal cladding **206**, **208** being 5 μm. This structure is located in a confinement containing a gas. This gas, when exposed to ionizing radiation of some kind, will dissociate into electrons with negative charge and corresponding ions with positive charge. If a potential difference (typically 500 V) is applied across the insulator/between the two metal clad sides of the composite mesh **202** structure, a dipole field F will develop in the holes **210**, sec FIG. 2*b* (the lines shown are equipotential lines, and thus the filed lines are perpendicular to these lines). Electrons released by the ionization in the gas will drift towards the high field through the holes/channels **210**, and will be focussed therein. The focussed electrons will then be amplified through avalanche multiplication of the electrons in the high electric field region. The amplified signal of electrons could be detected by e.g. a Multi-Wire Proportional Chamber (MWPC), a Micro Strip Gas Chamber (MSGC) or a Printed Circuit Board (PCB). With a device like this amplification factors above 10000 have been reached. It is also known to combine two GEM's by arranging them in a cascade at some distance, or in electrical contact.

Devices of this kind were originally developed for the detection of ionizing radiation in high-energy physics experiments. However, as indicated previously, these known devices are also suitable for detecting X-rays of diagnostic energies up to around 100 keV through conversions in the gas. At higher energies, the probability for the X-rays to interact in the gas will decrease and the efficiency will drop towards zero.

Turning now to FIG. **3** there is shown schematically a preferred embodiment of the detector according to the invention generally designated **300**.

It comprises a stack of alternating converters **302** and amplifiers **304**. The entire stack is located inside a housing (not shown) containing a suitable gas, e.g. Xe, although there is a large spectrum of possible gases to choose from like other noble gases such as e.g. Ar, Ne. Also mixtures of gases are conceivable, in particular it is a standard technique to mix in a so called quencher that will make the avalanches more controllable and make the detector less prone to sparks and discharges. Examples would be CO_2 or dimethylalcohol (DME). The gas or gas mixture may or may not be pressurized, or it could be provided at sub-atmospheric pressure. The higher the gas pressure, the more ionizations in the gas will take place per unit path length of a charged particle such as e.g. an electron.

The top cover **306** of the housing is preferably thin and light to maximize the number of low energy diagnostic X-rays reaching the gas volume at the top, i.e. as many of the X-ray photons as possible should be transmitted therethrough. A suitable material would be thin metal foil, e.g. Al, or the like. Other possible materials are polymers of various kinds, e.g. MYLAR®. Generally speaking materials with low atomic numbers are suitable. An at present preferred embodiment of the device according to the invention comprises as an amplifier device the above mentioned GEM (Gas Electron Multiplier) (for simplicity the perforations of converters and amplifiers have been left out). At present it is believed that the use of GEM's is the best mode of operating the invention.

The other component, the converter **302**, comprises a sheet of material having the ability to convert the incident photons into electrons through electromagnetic interactions. Preferably, a material with high cross-section for this reaction will be used. The converters have been positioned below each said GEM type structure. However the uppermost layer is an amplifier, for amplifing signals generated in the top gas volume **308**, just below the top cover **306**. In this volume low energy photons (diagnostic X-rays) will react and generate electrons.

The converter sheet **302** made of heavy metal is perforated (not shown in this figure), which are aligned with the holes (not shown) in said GEM structure. The converter sheet is preferably 0.1 mm to 1 mm thick depending on the field of application of the invention. The sheets may also be progressively thicker towards the bottom of the stack compared to the sheets in the top in order to match the higher occurrence of lower energy X-rays in the top layers relative to the bottom layers

These sheets are referred to as converter layers since the photons impinging in such a sheet will create charged particles (electrons and positrons) and the forward momentum of the photons will be transferred to the electrons, such that electrons will exit from the sheet into the gas volume **308** beneath the top cover **306**. There the electrons will cause ionization of the gas and give rise to the order of 10 electron-ion pairs on average. Those electrons will be collected and multiplied in the first amplification stage **304*a***. As indicated above, the amplifier in the structure may consist of said GEM type structure. The metal layers of the GEM's are biased with a voltage of typically 500 V etch. However, the voltage is variable in certain ranges such as from negative voltage (if you want to block the signal from above) up to 1000 V. By controlling the voltage certain beneficial effects are obtainable, which will be described below.

Each amplifier layer can be individually biased at a desired voltage/potential difference across the insulator with a suitable voltage source **310**. This could most easily be provided by arranging a series of variable resistors **312**, such that the voltage across each amplifier layer **304** simply is adjusted by adjusting the series resistance associated with that particular layer. Thus, each amplifier stage is coupled in a way such that it can be set at the desired potential by a common external voltage source. In the shown embodiment there is a resistor chain **312*a***, **312*b*** . . . **312*o***, coupled in series across the entire stack. The means for controlling the voltage across each amplifier is not critical and any other means that achieves the same result is useable within the scope of the invention. For example, each layer could of course be connected to an individual voltage source. In the shown example the external voltage across the entire stack is about 6000 V, and the voltage across each amplifier layer may be adjusted to between 0 and 1000 V.

For the top amplifier layer **304*a*** it is contemplated that the voltage bias for special purposes may be set to be reversed, i.e. in some cases the potential difference is set such that electrons scattered from the patient or other object and containing no relevant information, will not contribute to the signal.

GEM's would be only one possibility to achieve the desired charge collection and amplification that is needed in combination with the converter layers.

Another means of obtaining the desired charge collection and amplification would be to combine the converter layers (perforated with holes) with wire meshes **402** (see FIG. **4**). The potential difference between the wire mesh **402** and the converter should be high enough to start avalanche multiplication.

This double layer structure of "converter and amplifier" can be repeated a number of times, where a practical number could be 5–8, but could also be higher, or lower, for specific applications.

At the bottom of the stack of converter and amplifier layers there is a Printed Circuit Board (PCB) **314** for collecting charge and which is coupled to read-out electronics **316** that provide data to a control unit **318**, e.g. a computer. The signals can be routed to the edge of the board through state of the art multi-layer PCB's (see FIG. **5** which is a schematic illustration of a charge collector according to the invention comprising a PCB), and the electronics sensitive to the radiation (such as diodes, transistors or other semiconductor devices) can thus, in accordance with the invention, be positioned at the edge outside the radiation field and can even be shielded to be protected against scattered radiation. As indicated such PCB's per se are state of the art and in FIG. **5** a PCB based charge collector **500** is shown in a perspective view.

It may comprise 20 layers of an insulator such as FR4. Between each layer there are metal conductors provided, each of which are connected to one charge collection pad **502** each through holes, metal plated on the inner circumference, said conductors extending towards the edges of the board. The pads are preferably made of Cu, Au or Al, although other metals are conceivable, and are about 0.8 mm wide and about 5 μm thick. They are made using conventional photolithografic techniques well known in the art. The pads are distributed so as to correspond to the geometry of the holes in the converter and amplifier matrices, i.e a center to center distance of about 1 mm.

The most important feature of the PCB is that there is a large number of pads **502** distributed over the board. Each pad must have its own connection to an input of e.g. an ASIC **504**. If, as preferred, the ASIC's are mounted at the edges of the board, the PCB is made in a layered structure, wherein

the leads connecting the pads with the electronics are drawn in respective layers. The optimum design of such a PCB is made by so called auto-routing, a standard technique well known to the skilled man in the field of printed circuit board design. Suitable software for auto-routing can be obtained from Cadence, under the trade name SPECTRA.

Other types of charge collecting means are conceivable in less radiation intense environments, e.g. an ordinary CCD. Most likely different tools to achieve the charge collection and avalanche amplification will be used for different applications, the essential idea according to the invention being the mixing of layers of converters with layers for amplification and charge collection means to achieve an efficient detector for high energy X-rays.

Instead of collecting the electrons with pads on a printed circuit board and measure the charge for each pads as the signal proportional to the number of x-ray photons (or fluence) in one pixel there are other possibilities to read out the signal for each pixel. One way is to convert the electrons to visible photons at the bottom of the detector and have the bottom transparent to those photons.

In an ordinary avalanche in the gas there is at least as many photons produced as electrons and thus the photons may be produced in an amplifier at the bottom of the detector. Another way of producing the photons is to have the electrons incident on a fluorescent screen at the bottom of the detector where the electrons will induce emission of photons in this screen The photons created in any of these ways will in turn be detected by a sensor sensitive to photons such as for example a CCD. The photons may be guided to the CCD sensor through suitable optics such as mirrors and lenses.

In FIG. **6**, there is shown a schematic of a set-up **600** for radiation therapy with external X-ray photons or electrons. An accelerator (not shown) is situated in a neighboring room, and a beam of electrons B is directed through collimators towards the patient's body. If X-ray photons are desirable, a suitable target **602** is placed in the electron beam at appropriate location. If electrons are desired of course, no target is used. The beam (X-rays or electrons) is swept with a modulated intensity. A portal imager **604** according to the invention may be positioned either directly below the patient or below the treatment coach, as indicated in the figure. Also, there is provided a complementary diagnostic X-ray tube **606**, which is positioned above the patient. When the patient is exposed to diagnostic X-rays, the portal imaging device will function as a detector for diagnostic X-rays in the 50 keV range.

The function of a portal imaging device according to the embodiment shown in FIG. **3** will now be described with reference to the set-up of FIG. **6** and to FIG. **3**. We assume operation with photons, i.e. X-rays. Thus, for the production of therapeutic radiation, a linear accelerator is provided. It produces electrons in the energy range 1–50 MeV. These electrons are directed via suitable optics into the space where a patient to be treated is placed. A target (e.g. Be) is positioned such that the electrons impinging thereon produces X-ray photons, which are collimated and directed to the area on the patient's body where therapy and/or diagnosis is to be performed.

For diagnostic purposes, a standard X-ray tube positioned above the patient is used. The energy of such photons is around 50 keV. The photons exiting beneath the patient will impinge on the gas volume **308** at the top of the detector unit, comprising the stack of amplifiers **304** and converters **302**. A significant fraction of the diagnostic X-rays will interact in this gas volume **308**, mainly through the photoelectric effect. The ionization in form of electrons created by the photoelectron will be collected and amplified by the uppermost amplification structure **304***a*. Almost all diagnostic X-rays remaining after passing the gas volume **308** will be stopped in the first converter **302** (intended for high energy X-rays) and will create a negligible amount of detectable ionization. This first diagnostic image can be used for aligning the patient appropriately, e.g. if there should any risk of sensitive tissues being exposed to the highly energetic therapeutic X-rays that are to follow.

In the following moment the radiation therapy beam will be turned on, if there is no need to correct the position of the patient based on the information from the diagnostic X-ray image. The gas volume **308** will be more or less transparent to those high-energy X-rays. Since the gas volume **308** may still get hit by scattered electrons from the patient that does not contain much image information, it may be preferable to e.g. put the drift field to zero in the gas volume **308** to get rid of this background noise. The majority of these electrons will stop in the first converter layer **302***a*. The high-energy photons will penetrate into the stack and the photons with lower energy will predominantly convert in the top layers **302***a, b, c* while the photons with relatively higher energy will dominate in the bottom layers **302***n*, *n*-**1**, *n*-**2**. Secondary Compton photons will also penetrate down the stack and depending on the angle through which they are deflected, this will smear the position resolution as you go down in the stack. Since the contrast is higher for low energy photons the information content will presumably be higher in the top layers. By tuning the voltage determining the amplification for each layer it is possible to weight the contribution from the different layers to obtain a maximum contrast. It is also possible by way of comparing two images where higher and lower energy photons are weighted differently to roughly estimate the energy of the incident X-rays. From this estimate it is possible to deduce an elemental composition of the object. This may in particular be of value for non-medical applications, e.g. When looking for explosives in screening for air port security.

The attenuation of the x-rays in the object will mainly depend on the density (rho) and the atomic number (Z) of the object. Those two quantities are usually not possible to distinguish from each other, but since the dependence for each quantity is different as a function of x-ray energy this is actually possible with a detector that gives an estimate of the energy of the incident x-rays. As an example one could imagine first obtaining an image with the photons converting in the first half of the stack of converters/amplifiers weighted much higher comparing to photons converting in the second half. This will be an image predominantly made up of lower energy photons. Secondly one could register an image with the photons converting in the second half of the stack of converters/amplifiers. This will be an image consisting predominantly of higher energy photons. The number of x-ray photons detected in the two images will depend on the elemental composition of the object. This difference can be measured for different test objects of known composition. It is thus possible to calibrate the expected response for different materials. One can also compare the measurements to computer simulations of the spectrum and record images with one multiple weightings of the x-ray spectrum and compare the results to get a more detailed estimate of the elemental composition.

In FIGS. 7*a*–*b* a preferred embodiment of an amplifier/converter structure according to the present invention is disclosed, generally designated **700**.

FIG. *7a* is a cross section of one perforated sheet **700**, forming a composite layered dipole structure, comprising holes **702** through which electrons may move. The sheet is comprised of a first (or top) metal layer **704**, about 5 μm thick. This metal layer **704** has been deposited on an insulating material forming a first insulating layer **706**, similar to the known GEM structure described above with reference to FIG. **2**. Underneath the insulating layer **706** there is a thick metal layer **708**, which is at least one order of magnitude thicker than the top metal layer, in the shown embodiment it is 150 μm thick. Below the thick metal layer **708** there is a second insulating layer **710**, on which there is deposited a second (bottom) metal layer **712**. The layers **710** and **712** preferably have the same compositions and thicknesses as the layers **704** and **706**. The entire sheet is made by suitable known depostion methods.

When the composite sheet has been made, the holes **702** are made by etching. Being an unisotropic process, the etching will have the effect of creating "funnel" like holes, as is clearly shown in FIG. *7a*. Thus, the "entrance" opening **714** for electons has a smaller diameter that the "exit" opening **716**. The actual slopes of the inner walls of the holes **702** is not necessarily as shown in the figure, but will vary depending on the materials selected for the layers and on the particular etching process employed. The known GEM structure shown in FIG. **2**, having a much thinner overall thickness does not exhibit such outspoken funnel-like holes. This particular structure with such "funnel"-like holes **702** has certain benefits for the purpose of the invention, which will be described below.

The structure of FIG. *7a* will function as a composite amplifier/converter. Thus, as shown schematically in FIG. *7b*, which is an image obtained by simulation, a voltage is applied across the entire structure such that the first (top) metal layer **704** is at approximately +300 V, the thick converter layer **708** is at approximately 100 V, and the second (bottom) metal layer **712** is at −100 V. Of course these values can vary within relatively wide limits depending on where in the stack the actual structure is situated, and what one wants to achieve in the structure in question. The lines are equipotential lines, and thus the field has a direction perpendicular to the potential curves. As can be seen in FIG. *7b* there will be an electric field inside the holes **702**, the density of which is highest in the upper part of the holes **702**, i.e. in the region of the first insulating layer **706**. By virtue of the holes "flaring" out downfield, electrons passing through the holes **702** will have less probability of diffusing into the thick metal layer **708**, and thereby the efficiency of the structure becomes higher. The bottom part of the structure comprising insulating layer **710** and bottom metal layer **712**, does not function as an amplifier in the sense of the corresponding structure of layers **704** and **706**. Rather the function is to provide enhanced guiding of the electrons out from the holes **702** and to further prevent the potential diffusion of electrons into the converter metal layer **708**. Of course by suitable selection of voltage applied also the lower part of the structure could be used for amplification purposes.

These composite dipole layered structures **700** may be arranged in the same way as shown in FIG. **3**, just substituting the alternating converters **302*n*** and amplifiers **304*n*** for such a composite structure **700**. A set-up for use of the embodiment of the structure shown in FIG. **7** is disclosed in FIG. **9** and generally designated **900**.

Thus, a plurality of composite layered structures **902*a–d*, 904*a–d*** is stacked above each other enclosed in a housing (not shown). A top cover **906** is provided and a gas volume **908** is formed between the top cover and the first composite structure **902*a*, 904*a***. At the bottom of the stack there is provided a PCB **914** having read-out electrinocs **916** connected thereto, which in turn are coupled to a control unit.

The composite structures can be individually biased at a desired voltage/potential difference across the insulator with a suitable voltage source **910**, similar to the embodiment in FIG. **3**. This could most easily be provided by arranging a series of variable resistors **912*a–o***, such that the voltage across each amplifier **904** in the composite structure simply is adjusted by adjusting the series resistance associated with that particular layer. Thus, each amplifier stage is coupled in a way such that it can be set at the desired potential by a common external voltage source. In the shown embodiment there is a resistor chain **912*a*, 912*b* . . . 912*o***, coupled in series across the entire stack. The means for controlling the voltage across each amplifier is not critical and any other means that achieves the same result is usable within the scope of the invention. For example, each layer could of course be connected to an individual voltage source. In the shown example the external voltage across the entire stack is about 6000 V, and the voltage across each amplifier layer may be adjusted to between 0 and 1000 V.

In FIG. **8** an application of the invention for cargo screening is shown schematically in a top view. The set-up comprises a source of X-rays **800**, in the energy range up to 50 MeV, e.g. a linear accelerator. Collimators **802** are provided for collimating the X-rays. There is provided an arrangement for scanning/sweeping the beam over a relatively large area, indicated schematically by arrows S. Furthermore there is provided a detector **804** according to the invention, arranged such there will be a space **806** between the radiation source **800, 802** and the detector **804**, large enough for a large object, such as a lorry **808** to be positioned therebetween. Because the detector can be made only in a limited size, there is provided means for moving the detector in an X-Y plane such that when the radiation beam has scanned one area corresponding to the size of the detector, it can be moved so as to cover a previously unscanned area (the movement of the detector is indicated by arrows M). In operation of the system a large cargo carrying object, such as a container, truck, trailer etc, will be positioned in the space **806** between an X-ray source and a detector according to the invention. The radiation will be turned on and the interior of the object can be checked for its content, in relatively short time. As an alternative to move the detector, the entire object could be moved. A truck or other vehicle could e.g. be moved by its own engine.

The invention having thus been described, it should be understood that various modifications can be made without departing from the inventive concept, which is defined by the appended claims.

For example, the detector can be used to study dose distributions. This can be done in air or in a so called water phantom, which is a simulation of body tissue. For such

applications the material in the detectors are selected to mimic body tissue, i.e. polymers having carbon and nitrogen contents similar to that of living tissue.

Also, it is conceivable to use the device for imaging during electron therapy. In such a case of course the converter would not be operable since the therapeutic electrons themselves are detected.

It is also to be understood that the detector may be optimized by a skilled man for other types of particles, such as neutrons, protons, atomic nuclei of various kinds etc.

What is claimed is:

1. A detector unit for detecting photons in the energy range 1 keV to 100 MeV, comprising:

at least two non-gas converter layers stacked on one another and for interacting with incident X-ray photons and causing electrons to be emitted therefrom;

at least one amplifier coupled to each converter and adapted to interact with the electrons emitted from the converter to produce a multiplicity of secondary electrons and photons representing a signal proportional to the incident fluence of X-ray photons;

connectors connecting the detector to an electric field generating means for providing an electric drift field for secondary electrons in the detector; and

a sensor device arranged to receive said signal and provide an input to electronic signal processing means.

2. The detector as claimed in claim 1, comprising a housing enclosing said converter(s) and amplifier(s), and a gas provided inside said housing.

3. The detector as claimed in claim 2, wherein the housing comprises a top cover essentially transparent to low energy X-ray photons.

4. The detector as claimed in claim 2, wherein

a first of said at least two stacked converter layers is adapted to interact with and record incident X-ray photons of a first energy range, and

a second of said at least two stacked converter layers is adapted to interact with and record incident X-ray photons of a second energy range,

wherein each of the first and second stacked converter layers is adapted to selectively record a different energy range.

5. The detector as claimed in claim 1, wherein said converter comprises a sheet of a material with an average atomic number sufficiently large that a fraction greater than 1% of incident X-rays are converted.

6. The detector as claimed in claim 1, wherein said converter comprises a sheet of a heavy metal selected from the group consisting of Cu, Fe, Mo, Cr and W.

7. The detector as claimed in claim 1, wherein said amplifier comprises a composite dipole layered structure, said composite structure being perforated with holes.

8. The detector as claimed in claim 7 wherein said composite dipole structure comprises a sheet of an insulating material which is metal clad on both sides.

9. The detector as claimed in claim 8 wherein said converter comprises a perforated sheet and wherein each perforation has a dimension such that it covers at least one each of said holes in said amplifier.

10. The detector as claimed in claim 7, further comprising connectors connecting each amplifier to a voltage source for applying a voltage across each layer to create an electric field over the dipole structure, the density of which is higher within said holes, thereby to cause a drift of electrons through said holes.

11. The detector as claimed in claim 1, wherein said converter and said amplifier are integrated in one unit by the provision of a composite dipole layered structure comprising a sheet of an insulating material which is metal clad on both sides, wherein at least one of said metal claddings is substantially thicker than the sheet of insulating material, said thicker metal cladding acting as a converter.

12. The detector as claimed in claim 11 wherein said thicker metal cladding is provided on the bottom side of said insulating sheet, and wherein the upper metal cladding is sufficiently thin to achieve an electric field for providing efficient charge collection.

13. The detector as claimed in claim 11 comprising a central metal layer on both sides of which there is provided an insulating layer, and wherein the respective insulating layers each are provided with a metal film, wherein the central metal layer is thicker than each insulating layer, and wherein each insulating layer is thicker than each metal film.

14. The detector as claimed in claim 13 wherein said composite dipole layered structure is perforated with holes.

15. The detector as claimed in claim 14, wherein said holes have an entrance opening for electrons and an exit opening wherein said exit opening is wider than said entrance opening.

16. The detector as claimed in claim 1, having a composite dipole layered structure, comprising a sheet of an insulating material which is metal clad on both sides, wherein said insulating material acts as a converter.

17. The detector as claimed in claim 1, wherein said connection means comprise a resistor chain coupled in series across the entire detector unit including converters and amplifiers such that the voltage across each amplifier and converter is selectable and variable.

18. The detector as claimed in claim 1, wherein said converter and said amplifier are integrated into one composite layered structure, such that at least one of said layers in said amplifier constitutes said converter.

19. The detector as claimed in claim 1, wherein said sensor device is a charge collection device arranged to collect said secondary electrons.

20. The detector as claimed in claim 1, wherein said sensor device is an optical sensor device arranged to detect said photons.

21. A system for X-ray therapy and diagnosis, comprising:

at least one source of X-rays;

collimators for said X-rays for providing a defined amount of radiation to a patient; and

a detector as claimed in claim 1.

22. A detector unit for detecting photons in the energy range 1 keV to 100 MeV, comprising:

at least two converter layers stacked on one another and adapted to interact with incident X-ray photons and to cause electrons to be emitted therefrom;

at least one amplifier coupled to each converter and adapted to interact with the electrons emitted from the converter to produce a multiplicity of secondary electrons and photons representing a signal proportional to the incident fluence of X-ray photons;

connectors connecting the detector to an electric field generating means for providing an electric drift field for secondary electrons in the detector; and

a sensor device arranged to receive said signal and provide an input to electronic signal processing means,

wherein said amplifier comprises a wire metal mesh, and wherein there is provided connecting means for connecting a voltage source to apply an electric potential between the converter and said wire mesh.

23. A detector unit for detecting photons in the energy range 1 keV to 100 MeV, comprising

a housing having walls, a top cover and a bottom and enclosing a gas;

a plurality of integrated converter and amplifier structures arranged in a stack in said housing;

a charge collection device arranged at the bottom of the housing;

connection means comprising a variable resistor chain coupled in series across the entire detector, connectable to an external voltage source;

electronic read out devices coupled to said charge collection device for providing an input to a control unit; wherein

said integrated converter and amplifier structures each comprise a central metal layer on both sides of which there is provided an insulating layer, and wherein the respective insulating layers each are provide with a metal film forming a composite dipole layered structure, wherein the central metal layer is thicker than each insulating layer, and wherein each insulating layer is thicker than each metal film, and wherein said composite dipole layered structure is perforated with holes; said holes having an entrance opening for electrons and an exit opening wherein said exit opening is wider than said entrance opening.

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Advances in Gas Avalanche Photomultipliers*

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Abstract

Gas avalanche detectors, combining solid photocathodes with fast electron multipliers, provide an attractive solution for photon localization over very large sensitive areas and under high illumination flux. They offer single photon sensitivity and the possibility of operation under very intense magnetic fields.

We discuss the principal factors governing the operation of gas avalanche photomultipliers. We summarize the recent progress made in alkali-halide and CVD-diamond UV-photocathodes, capable of operation under gas multiplication, and novel thin-film protected alkali-antimonide photocathodes, providing, for the first time, the possibility of operating gas photomultipliers in the visible range.

Electron multipliers, adequate for these photon detectors, are proposed and some applications are briefly discussed.

Presented at **Beaune99**, The Second International Conference
On New Developments in Photodetection
Beaune, France, June 21-25, 1999

(To be published in Nuclear Instruments and Methods A)

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* Talk by A. Breskin, dedicated to the memory of the late Pierre Besson.

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1. Introduction

In recent years there have been considerable advances in photon detectors, motivated by the ever-growing complexity of their potential applications. High-resolution localization of light, over a broad spectrum ranging from far UV to the IR, often down to a single-photon level, is requested in various basic and applied fields. Numerous examples can be found in particle and nuclear physics, astrophysics, medical imaging etc.
Present photon detection techniques range from tiny cryogenic detectors, employed in astrophysics, through a variety of small-area solid-state detectors, to vacuum-based devices - reaching dimensions of up to half a meter in diameter. The latter are photomultipliers developed for large under-water astro-particle experiments and are not position-sensitive. Commercially manufactured position sensitive vacuum photomultipliers are limited in size to a few inches in diameter, suffer from a degraded response in moderate magnetic fields and are rather expensive. Intensive research and development work is taking place in the more recently introduced hybrid photo detectors (HPD) [1]. These vacuum-operated devices could be, in principle, more immune to magnetic fields; 5 inch in diameter HPDs, with a highly pixelized readout, are being developed for particle identification by the Ring Imaging Cherenkov (RICH) technique, in the field of particle- and astro-particle physics [2].
In most experiments, the RICH technique requires the coverage of very large photon detection areas, typically of several square meters, good localization accuracy and high sensitivity to single Cherenkov photons. Numerous other applications, such as photon recording from large arrays of scintillators or scintillating fibers also require fast, large area, photon detectors, and often immune to magnetic fields.
Therefore, a large variety of gas-

3], have been developed over the last two decades and are successfully employed in numerous experiments. The first generation of such detectors consisted of wire chambers, filled with an UV- photosensitive gas (TEA, TMAE) [4]. The new generation of faster, large-area single-photon imaging detectors consists of thin-film CsI UV-photocathodes, coupled to gas avalanche electron multipliers [5]. These devices are already successfully employed in RICH detectors, in some particle physics experiments, and are under construction in many others [6].
We discuss below the main factors governing the operation of this new family of gas avalanche photomultipliers and their principal properties. We summarize the recent progress made in UV and visible-range photocathodes, capable of operation under gas multiplication and suggest some preferable electron multipliers. Some applications are discussed.

2. General considerations

In gas avalanche photomultipliers with solid photocathodes (Fig. 1), photoelectrons are emitted into a gas. Depending on the type of electron multiplier coupled to the photocathode and on the electric field at the photocathode surface, they either drift to the multiplying electrode or experience a multiplication process at their emission location. In both cases, the surface photo-conversion, followed by surface emission, make these detectors very fast and insensitive to the radiation incidence angle, as

opposed to photon detectors where photo-ionization occurs within the volume of a photosensitive gas [7].
Unlike vacuum devices, these detectors can operate under high magnetic fields [8]. The operation under atmospheric gas-pressure permits constructing large area, thin, flat detectors of sizes limited mainly by the photocathode production technology. Highly integrated readout electronics [9], developed for particle physics applications, permits the conception of highly pixelized position sensitive photon detectors, capable of operation at high photon flux and under MHz frame rates.
The photon detection efficiency of these gas avalanche photomultipliers, over a given spectral range, depends on three factors: the photocathode quantum efficiency (QE), electron back-scattering from the photocathode into the gas [10] and the efficiency of detecting single electrons with the gas multiplier. The latter depends on the multiplier gain, its signal shape (which is multiplication-mechanism dependent) and on the readout electronics (integration time, noise).
The long-term stability principally depends on the photocathode, which may be degraded either by chemical reaction with gas impurities or by accumulated impact of photons and avalanche-originated ions. As discussed below, UV-photocathodes are generally chemically stable, while visible-range ones can be protected by coating them with thin films. Ion aging can be considerably reduced by a proper choice of the electron multiplier and the operation conditions.

3. Photocathodes

3.1. UV spectral range

The best known photocathode for the UV range is CsI. An extended review of its properties is given in ref.[5]. CsI has high absolute QE, of the order of 40% at 150nm, in a reflective mode; its red boundary cutoff is around 210nm, as shown in Fig. 2. Reflective CsI photocathodes, of typical thickness around 500 nm, are chemically stable; they can be exposed to ambient air for 30-60 min, without noticeable degradation of their emission properties. The chemical stability is of prime importance when installing such large area photocathodes within the photomultipliers, usually under inert gas flushing conditions.
CsI gaseous UV detectors were first applied as readout elements for Xenon-filled scintillation chambers [11]. Large-area CsI photon detectors have shown stable long-term behavior and adequate single-photon sensitivity under accelerator investigations [12]. Such detectors, of sizes exceeding a square meter, are under construction for the RICH detectors of the CERN-LHC-ALICE experiment [13]. Several other nuclear and particle physics experiments (GSI-HADES, CERN-COMPASS and others) have adopted this technique. It should be noted that the QE of 60 x 40 cm^2 large CsI photocathodes for ALICE, evaluated from experimental Cherenkov events, is about 20-30% lower for wavelengths below 180 nm, compared to the data shown in Fig.2 [13].

Two other UV-sensitive photocathodes, CsBr and chemical vapor deposited (CVD) diamond films, have recently been investigated. Their typical absolute QE distributions are also shown in Fig. 2.

CsBr photocathodes have not drawn any particular interest in the past, probably because of their spectral response which is limited to the far UV (cutoff at 0.1% QE around 190 nm)[14

photodetectors are requested, CsBr could be an excellent candidate. As shown in Fig.2, the QE of a CsBr film, which was subject to a post-evaporation thermal annealing under vacuum at 70 ^{0} C for about 6 hours, reaches values of the order of 30% at 150nm [14]. The quantum photoyield of our as-deposited CsBr films is inferior, with a cutoff at 175nm; it is similar to that previously published [15], as shown in Fig.3. Our recent investigations of reflective and transmissive CsBr photocathodes have shown that this material behaves rather similarly to CsI. Reflective photocathodes can be handled in ambient air for a few tens of minutes, with no apparent degradation and the surface aging of CsBr by intense photon flux and by ion impact also occurs after equivalent irradiation doses in both materials [14]. Charge multiplication in a CsBr-based parallel-plate gas avalanche detector was stable up to the investigated gains of the order of 10^4, though the surface resistivity of CsBr is apparently larger than that of CsI [16].
Recent investigations of the surface morphology of very thin (20-75nm) transmissive alkali halide films, clearly indicate their sensitivity to minute exposure to moisten gases, as shown in Fig.4 [17]. Particular care should therefore be taken while installing such transmissive photocathodes within the detectors.

CVD diamond films are also very interesting photosensitive materials [18]. Like mono-crystal diamonds, they have a wide energy band gap, of 5.47eV; they also have negative electron affinity (NEA), after surface hydrogenation [19]. Though having lower QE in the far-UV, compared to CsI and to CsBr, diamond photocathodes could find applications in detectors operating in a demanding environment, because of their known high chemical stability, radiation hardness and capability of operation under very high temperatures (hydrogen desorption occurs only above 800^{0}C). The QE curve shown in Fig.2 is for a diamond film whose surface was subject to hydrogen plasma etching. This establishes hydrogen surface termination, activating NEA, and was found to enhance the QE of CVD-prepared diamond films, by a factor of two[20]. Such surface treatment, yielding QE values of the order of 12% at 140 nm, is rather stable for short exposures to ambient air; long exposures, however, cause surface oxidation, resulting in positive electron affinity and therefore, loss of QE [20,21]. However, the photoemission properties could be recovered by repeated hydrogen-plasma etching. Other surface treatments, such as Cs-termination, could activate superior NEA on diamond films compared to that with hydrogen [22,23]; however the stability of Cs-terminated surfaces, under gas multiplication conditions, is still questionable.

3.2.Photocathodes for the visible range

The most important applications of gas avalanche photomultipliers, are, no-doubt in the visible spectral range. Here, alkali-antimonide photocathodes, in particular Cs_3Sb and K-Cs-Sb, are widely employed in vacuum-photomultipliers. These materials are extremely reactive to even minute amounts of impurities, e.g. oxygen and moisture. Therefore, some attempts at operating such photocathodes under gas multiplication [24,25], were not pursued.
A possible solution for avoiding the degradation of the reactive alkali-antimonide photocathodes is to coat them with thin protective films [26], allowing for the transport of photoelectrons, while preventing contact between the gas molecules and the photocathode. Intensive research of adequate protective materials for Cs_3Sb and

K-Cs-Sb photocathodes, coating conditions, electron transport properties, sensitivity to impurities, aging etc. have yielded very satisfactory results [27-30].
The coating film thickness is a compromise between the need for efficient photoelectron transmission (high QE) and the request for high stability under exposure to the counting gas. The best results were obtained with CsI and CsBr coating films [30], known for their good electron transport properties, reflected here by relatively small electron attenuation lengths (18 nm for CsI and CsBr, at 300 nm wavelength [31]).
Fig.5 shows typical distributions of the absolute QE, as function of wavelength, for bare K-Cs-Sb photocathodes and for ones coated with 25 and 30 nm thick CsI and CsBr films, respectively. The respective absolute QE values of these two coated photocathodes are of the order of 4% and 7% at 320 nm. These values represent about 4 to 6 times QE attenuation by the films, compared to the initial QE of the bare photocathode. These rather thick film coatings were chosen so as to protect the photocathodes against exposure to large amounts of oxygen. Indeed, Fig.6 shows the behavior of a bare and of two coated photocathodes, of different CsI film thickness, under exposure to oxygen. While the QE of the bare photocathode totally decays at 10^{-5} Torr of oxygen, the 20 nm thick film-coated one can withstand a 5 min exposure to 0.1 Torr, with a residual QE value of 10%. A 25-nm thick CsI film totally protects the photocathode, up to 150 Torr of oxygen, at the expense of further attenuation of the QE. However, this coating thickness permitted the storage of the photocathode at 150 Torr of oxygen, with practically no decay, for more than an hour [30]. Higher QE values are obtained with thinner coating films, which may still provide sufficient protection for operation of the photocathodes in ppm-purity level gases.
It should be stressed, though, that the alkali-halide coating-films do not provide sufficient protection against moisture; this is due to their hygroscopic nature, which tends to affect the surface continuity [17]. Other materials are being evaluated for protection against moisture. Some organic films were also studied for surface protection during production or transfer [32,33].
More results and details about visible-photocathode production and coating are given elsewhere [27-30,34].

4. Electron multipliers

As briefly discussed above, the type of electron multiplier coupled to the photocathode could play a decisive role. On one hand, it should provide high gas amplification for enhanced single-photon sensitivity; on the other hand, its operation mode should prevent an accelerated degradation of the photocathode and limit its exposure to avalanche-generated, photon- and ion-feedback effects. In addition, the photoelectron extraction efficiency strongly depends on the counting gas and on the electric field at the photocathode vicinity (electron back-scattering process). High electric fields enhance inelastic processes (excitation, ionization) on the account of elastic scattering, thus allowing for maximal electron extraction efficiencies, close to that in vacuum [10]. At electric fields above 10-20 $Vcm^{-1}Torr^{-1}$, gas multiplication starts in most gases; under these conditions, in addition to full extraction efficiency, the detector response is faster, due to the absence of electron drift and diffusion. However, a high field could have a serious drawback; the increased velocity of the back-drifting ions, impinging on the photocathode, may cause a faster degradation of its surface, by sputtering. The ion velocity can be reduced by a proper choice of the gas mixture [35].

The worst choice for an electron multiplier would be the parallel-plate avalanche chamber, where a high field is applied between the photocathode and an anode electrode. Here, all avalanche-induced ions sputter the photocathode at high velocity. Multi-step avalanche chambers, where the avalanche process occurs in successive parallel-grid elements, would be a better choice; it offers very high gain and only a fraction of the avalanche ions return to the photocathode [36]. Large-area CsI-based photon detectors generally employ MWPCs [6,13]. Here, the ions have high velocity at the vicinity of the anode wires, but they slow down at the photocathode region. Also, due to the field line distribution, only a fraction of the ions reach the

suffer from counting rate limitations; this could be a serious drawback in some applications, e.g. in medical imaging etc. Low-pressure operation of such multipliers is characterized, among others, by a fast ion clearance from the avalanche region and therefore by lack of space-charge effects [37]. It provides high gas gains and high rate capability, but at the expense of shorter photocathode lifetime due to more energetic ion sputtering [36].

Modern micro-pattern gas electron multipliers [38] could provide an adequate
39 40 41], and other compact
multiplying electrodes have been employed in combination with CsI photocathodes. They consist of precise and dense anode and cathode patterns (strips, dots etc.), 50-200 micron distant, deposited on insulating substrates. Due to the particular electric field geometry, a large fraction of the avalanche ions, created at the vicinity of the anode patterns, are collected at neighboring cathode electrodes, rather than returning to the photocathode (Fig. 1). This rapid ion clearance from the avalanche region results in high counting rate capability and in fast electrical pulse buildup. It has been demonstrated that the low-pressure operation of such micro-pattern devices provides, in addition, very high gains and fast response [39,41], as shown in Fig.7.
42 - 43] and
44] multipliers, where the avalanche develops over
very small distances (50-100 microns).

The GEM particularly, could suit our application, due to very special electrode geometry. This simple multiplier consists of a compact array of small apertures in a metal-coated, 50-micron thick, Kapton foil. The apertures, of 30-100 micron in diameter, are typically spaced by 150-200 microns. A potential difference of a few hundred volts across the GEM foil leads to avalanche formation within the apertures, reaching amplification factors above 1000 in a single element, both at atmospheric [45] and low [46,47] gas pressures. Very high gains, exceeding 10^5, and stable operation have been reached in GEM-based photomultipliers, by cascading a GEM with another multiplying element [46,47] (see Fig.8) or by cascading several GEMs operating even with noble gas mixtures [35,48] (see Fig.9).

The GEM inserted in a gas avalanche photodetector, between the photocathode and the following multiplication elements, will play a multiple role:

- It would transmit photoelectrons into the multipliers, while screening the photocathode from avalanche-induced feedback photons, as demonstrated in ref.46 (Fig.10).
- In some electric field configurations, the GEM would block a fraction of the back-drifting ions.
- Some gain on the GEM will permit reducing the gain on the following multiplication elements, leading to more stable operation. It will allow for higher total gain and therefore higher sensitivity to single photons.

- The almost complete elimination of photon feedback effects in multi-GEM structures, permits, for the first time, reaching very high gains (> 10^5) in noble gas mixtures [49,35,48]. This should permit the operation with sensitive alkali antimonide visible photocathodes.
- The thin GEM electrode permits very fast avalanche development, leading to fast signals [35,47] and therefore to good time resolution.
- The deposition of a photocathode on top of the GEM surface (Fig.11) [46] should permit an operation free of photon feedback effects.

5. Conclusions

Gas avalanche photomultipliers, with their numerous advantages, have become interesting potential tools for high resolution, fast photon imaging tasks in numerous applications. In the UV range, very large area (square meters) CsI-based gaseous imaging devices are under construction for RICH detectors. CsBr and CVD diamond photocathodes have interesting properties in the far UV (solar-blind) range. The quantum efficiency of the diamond films can be enhanced by surface modifications, but most probably at the expense of chemical stability.

Ways have been paved towards imaging of visible light with gaseous photomultipliers. Conditions were found for protecting alkali-antimonide photocathodes against oxygen, with 25-30 nm thick alkali-halide (CsI, CsBr) films. Coated K-Cs-Sb photocathodes, having QE values of 5-6% in the 300-350nm spectral range, can withstand long exposures to over 100 Torr of Oxygen. However good protection against moisture is more problematic, due to the hygroscopic nature of alkali-halide films. Other coating films, among them organic materials, are investigated for possible protection against moisture. Higher QE values were reached with thinner protective films, which would suit the operation of these photomultipliers in high purity gases.

Alkali-halides and alkali-halide-coated visible photocathodes undergo moderate aging under intense photon illumination and gas multiplication. In our estimation, this should not prevent their use, even at extreme photon imaging conditions.

The damage induced by avalanche ions can be largely reduced by employing modern micro-pattern electron multipliers. In devices having electrode patterns printed on insulating substrates (MSGC, MDOT, MGC) or in others, where multiplication occurs within tiny apertures (GEM), or within fine-grid structures (MICROMEGAS, micro-CAT), one can find operation conditions for preventing most of the avalanche ions from reaching the photocathode. Of particular interest is the recently proposed multi-GEM multiplier.

Besides the present application of UV-photon imaging in Ring Imaging Cherenkov (RICH) Detectors, gas avalanche photomultipliers have a broad spectrum of potential applications. These fast, large area imaging detectors, capable of operation at repetition rates superior to a MHz/mm^2 and under high magnetic fields, could be employed for photon recording from large scintillator and scintillating fiber arrays. The latter have numerous applications in particle and nuclear physics and in medical diagnostics apparatus. An application of visible-light gas avalanche photomultipliers for digital mammography is in progress, within a European Union project [50].

Acknowledgements

The work was partially supported by the Israel Science Foundation, The Israel Ministry of Science and Arts and the European Union. The research on photoemission from diamonds was done in close collaboration with Prof. A. Hoffmann, Prof. R. Kalish and A. Laikhtman from the Technion and with Dr. Y. Lifshitz from SOREQ NRC in Israel. We express our thanks to them. We would like to thank Prof. F. Sauli and Dr. A. Sharma from CERN for their collaboration on the GEM project. A. Breskin is the W. P. Reuther Professor of Research in the Peaceful use of Atomic Energy.

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Figure Captions

Figure 1: The principle of the gas avalanche photomultiplier. A photon-induced electron is emitted from a solid photocathode into the gas. Avalanche multiplication takes place in the electron multiplier, close to an anode of a micropattern device. In this configuration, most avalanche-induced ions are collected on the neighboring cathodes and some drift to the photocathode.

Figure 2: Typical quantum efficiency plots (in vacuum) of annealed CsI [5], CsBr [14], and of hydrogen-terminated CVD-diamond [20] photocathodes.

Figure 3: Absolute quantum efficiency plots (in vacuum) of a 500 nm thick CsBr photocathode, as evaporated and after an annealing of 3 and 6 hours at 70^0C. Data of Taft and Philipp [15] is shown for comparison.

Figure 4: SEM views of thin alkali-halide photocathodes deposited on CaF_2/Cr substrates. a) a 20 nm thick CsI film, as-evaporated; b) same as (a) after exposure to air for 9 minutes; c) a 75 nm thick CsBr film, as evaporated; d) same as (c) after exposure to Argon at 80% humidity for 1 minute. The full scale, in all cases is 5μm.

Figure 5: Typical absolute quantum efficiency spectra of K-Cs-Sb photocathodes, bare and coated with 300 250

Figure 6: The evolution of the absolute quantum efficiency of K-Cs-Sb photocathodes exposed to oxygen. Shown are the results of bare and coated photocathodes with 200 and 250 thick CsI films, as a function of the residual oxygen pressure at 312nm. Each data point represents 5 minutes of exposure to oxygen followed by quantum efficiency measurement in vacuum.

Figure 7: Fast single electron pulses obtained from a) a Microdot gas avalanche chamber operated in 60 Torr of C_3H_8; b) A multiwire proportional chamber (MWPC) operated in 40 Torr of i-C_4H_{10} and c) the same MWPC coupled to a GEM (at gain 250). All pulses measured with the same fast current amplifier.

Figure 8: A gas avalanche photomultiplier comprising of a GEM electron preamplifier, inserted between the photocathode and the electron multiplier (here a MWPC). The GEM enables reducing the gain on the MWPC and screens the photocathode from photon feedback.

Figure 9: A multi-GEM photomultiplier consisting of a cascade of GEMs coupled to a photocathode. Each GEM operates at a low gain, resulting in a high total gain. The resulting avalanche induced pulses can be recorded on a printed circuit board, without any additional multiplication. The GEM elements screen the photocathode from photon-feedback and reduce ion-feedback effects.

Figure 10: Photon-feedback in 40 Torr methane: a) A MWPC coupled to a CsI photocathode; has an intense photon-feedback, gain $<10^5$; b) a MWPC+GEM (see figure 9), a reduced photon feedback and gain $>5\times10^6$

Figure 11: A photon-feedback blind detector: photons are converted on a reflective photocathode deposited on a GEM. The photoelectron is focussed into the GEM holes, is preamplified and further amplified in the MWPC. Avalanche-induced photons cannot reach the photocathode.

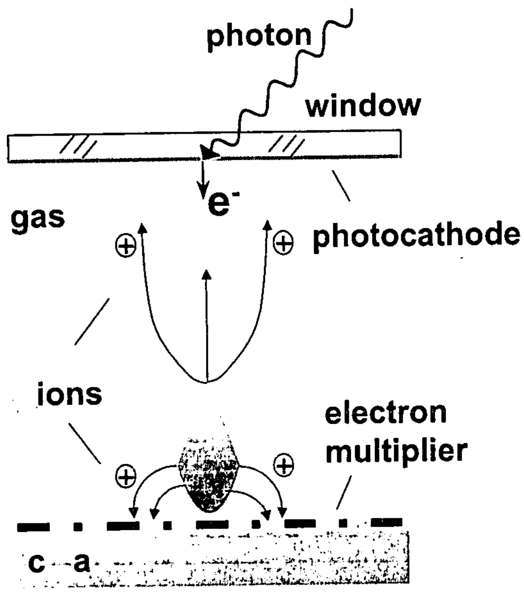

photon
window
e-
gas
photocathode
ions
electron
multiplier
c
a

Figure 1

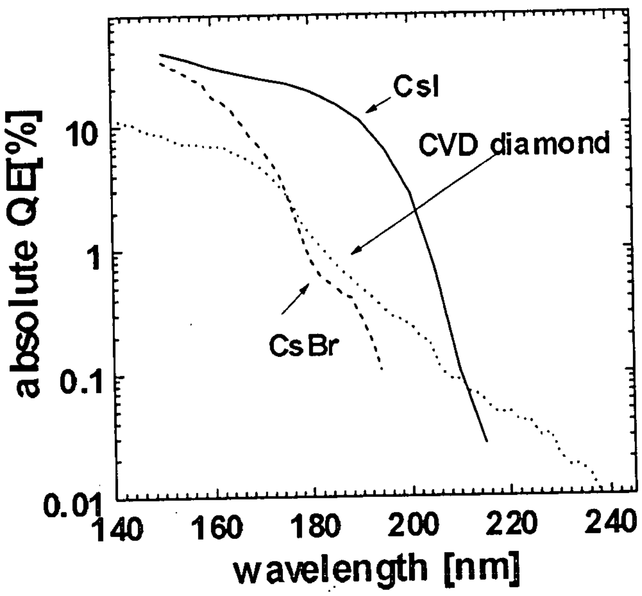

absolute QE[%]
10
1
0.1
0.01
140
160
180
200
220
240
wavelength [nm]
CsI
CVD diamond
CsBr

Figure 2

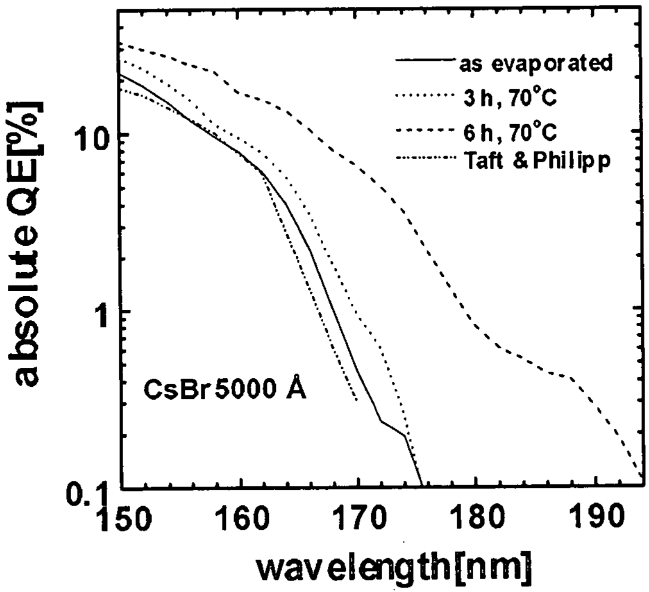

as evaporated
3 h, 70°C
6 h, 70°C
Taft & Philipp
absolute QE[%]
10
1
0.1
CsBr 5000 Å
150
160
170
180
190
wavelength[nm]

Figure 3

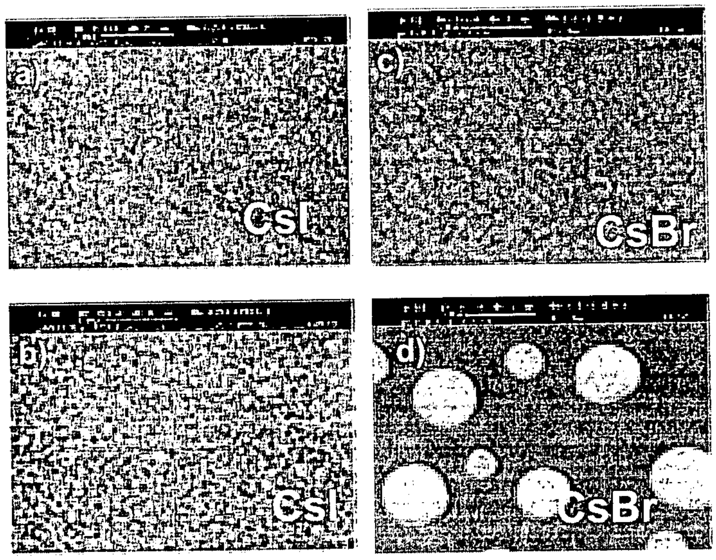
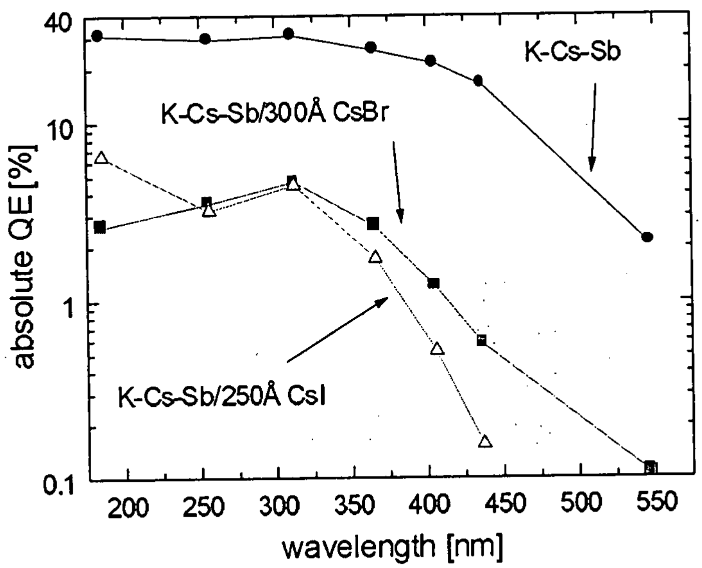


Figure 4



K-Cs-Sb
K-Cs-Sb/300Å CsBr
K-Cs-Sb/250Å CsI
absolute QE [%]
40
10
1
0.1
200 250 300 350 400 450 500 550
wavelength [nm]

Figure 5

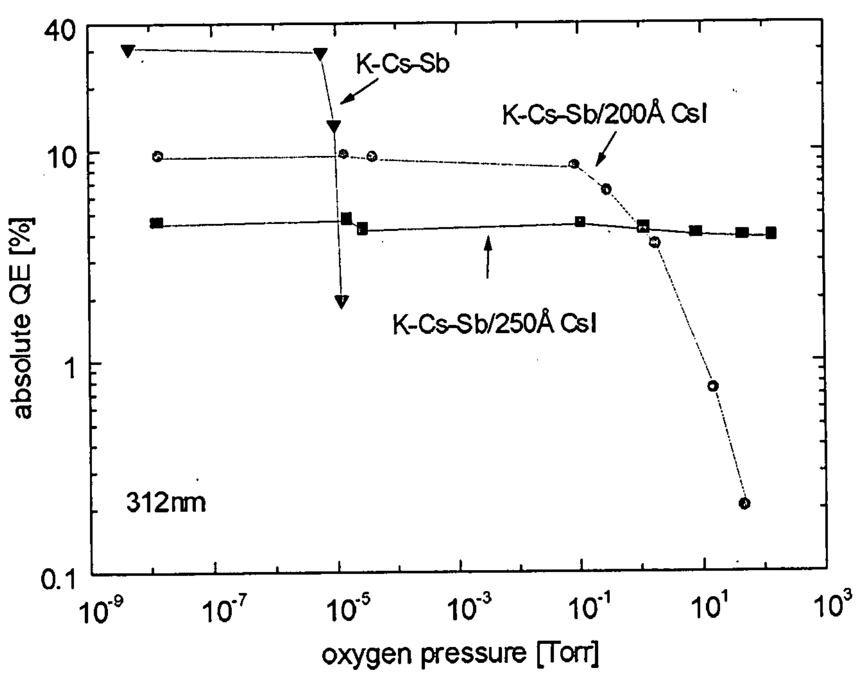

40
10
1
0.1
absolute QE [%]
K-Cs-Sb
K-Cs-Sb/200Å CsI
K-Cs-Sb/250Å CsI
312nm
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
oxygen pressure [Torr]

Figure 6

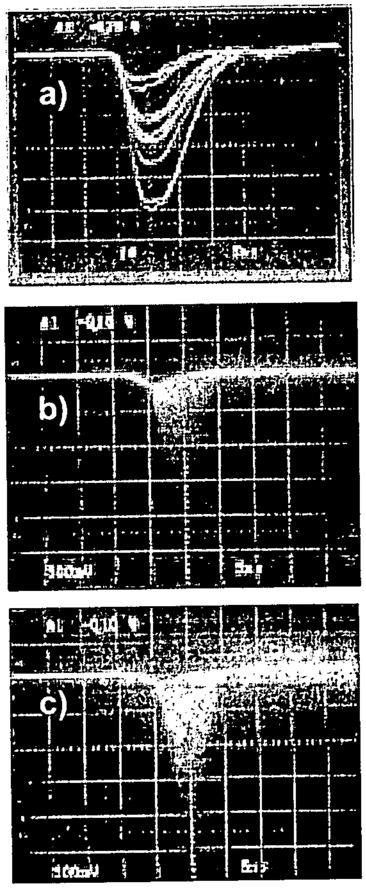


Figure 7

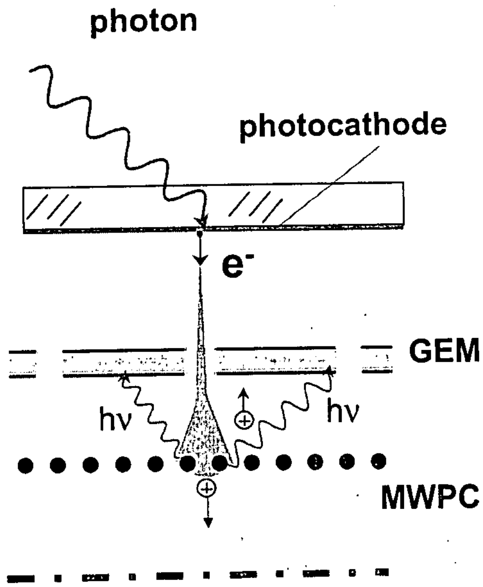


Figure 8

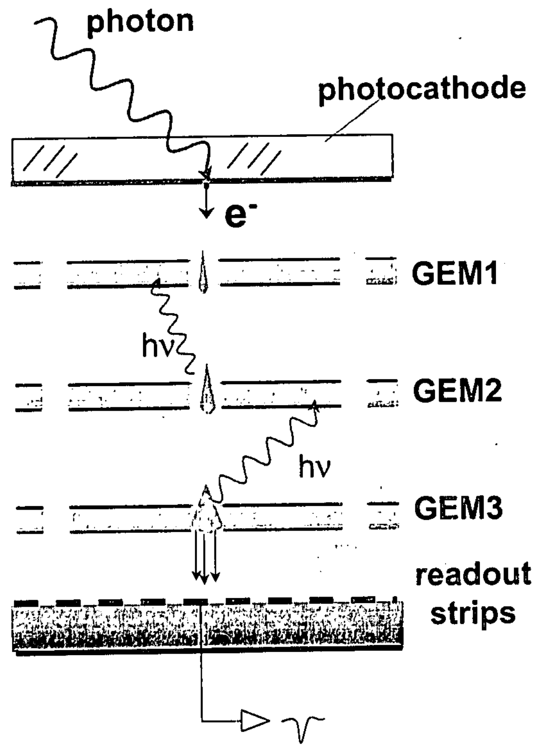


Figure 9

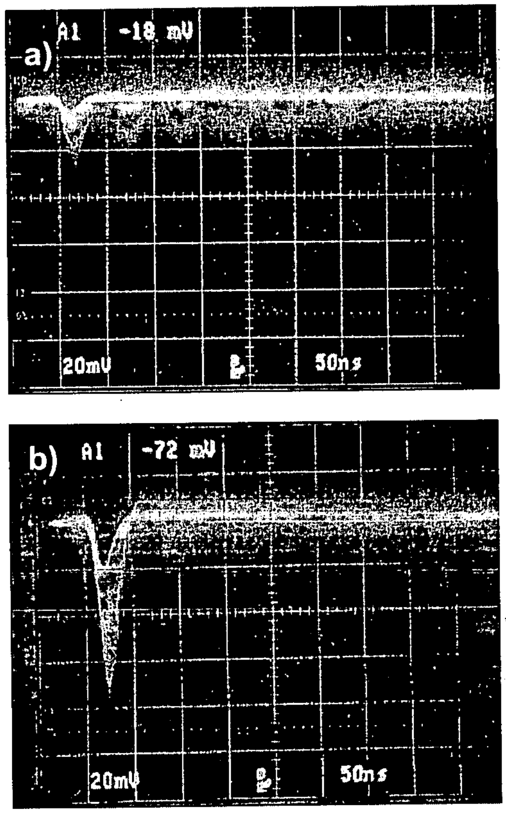


Figure 10

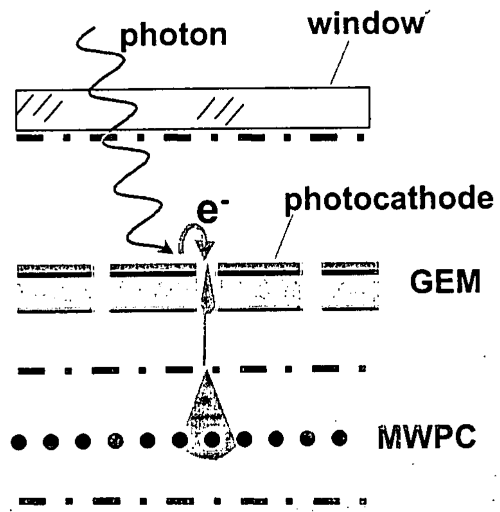


Figure 11